Department of Forestry

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Mathematical Programming for Advanced Forest Management Planning in Fiji

Optimising Harvest Wood Allocation in the Mixed-hardwood Plantations using Linear Programming Model

by

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Abstract

Short to long term forest management planning of native forests and forest plantations in many developing countries has proven a difficult undertaking. Beside the inherent social difficulties relating to land tenure, there are always inadequate personnel and limited relevant resources to carry out appropriate planning for wood and non-wood demands with the changing market scenarios. Adoption of appropriate decision support systems from countries where they have been successfully used may resolve some of the uprising conflicting demands on our forest resources.

The SCHEDULER System, a computer based linear programming scheduling model was used in a case study concerning the allocation of wood from four hardwood plantation harvest areas to a number of processing centres in Fiji. This decision support system has provided insights into forest management problems, in particular, the need for a sound and central information base. To maximise the timber value or present net value, wood allocation to the integrated mills in the proximity of the harvest areas must be encouraged. Findings of the short and medium term management alternatives have suggested that the country must change its approach to forest planning. Promotion of divisional and station level planning could play an effective role toward better decisions and a more realistic national plan.

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Chapter 1

1. INTRODUCTION

The myth that "trees are renewable" has little or no meaning to most rural dwellers in the Fiji Islands. Local trees and native forests are part of their ancestral heritage to provide basic necessities for the current and coming generations. Blessed by the abundant forests, so it seemed, most landowners have exploited their forests as an alternative source of income, only to realise that the outcomes have made them worse off. Other landowners acknowledged their forests as nothing but a hindrance to their subsistence farming and agricultural development.

The combined effect of these two motives have contributed significantly to the rapid decline in forest cover. With less than 50% (855,000 ha) of the total land area under forest in late 1950's, the Forestry Department was enacted to established two reforestation programs.

The long term objectives of the reforestation programs were to improve the biological and economic value of grasslands and logged over rainforests and to sustain wood supply for domestic demands and export markets, with the intention of preserving rural community areas as viable working environments. The encouragement of rural participation in a decentralised forest industry is hoped to dissuade urban drift. The gradual reduction of native forests exploitation to its ultimate cessation in the near future, countered by sustained production from maturing man-made forests has made forest planning process more complex than ever before and highly dynamic. To manage these plantations in an environmentally, economically and socially sustainable manner, the decision making process may benefit by using elements of "*Management Science or Operations Research*" with consistent integrated and multidisciplinary planning.

This study represents the introduction of Management Science, in particular, mathematical programming (MP), into forest management planning in Fiji and the decision making associated with man-made mixed-hardwood plantations. Initially, this would require the identification of a suitable mathematical programming technique to assist in selecting optimal forest management strategies and activities to satisfy management goals and objectives.

In the case study, mathematical programming was used to investigate certain single and multiple-use objectives of forest management. In addition, appropriate management strategies for the next two to three decades were identified. The study was not intended to absolutely resolve the problems of forest management or dictate the decisions to be taken. It is essentially a comprehensive evaluation of selected mathematical programming models and their technical and economic efficiency as working tools.

In the study, a system of computer programs called the SCHEDULER System, developed by Schurr and Davis (1989) was used. The SCHEDULER System is designed to optimise management objectives within economical and physical constraints with a linear programming package (LINDO) and additional software. Two techniques, linear programming for single objective and goal programming for multiple objectives, and their solution process have been investigated.

Findings of the study provide potential guidelines in formulating Fiji's Timber Harvesting Schedules as part of Forest Management Plans at the National level and Operation Plans at the Divisional level. Practical applications of mathematical programming techniques have been demonstrated and presented in the case study. Mathematical programming, in particular the linear programming model that provides a potential analytic tool for even-aged mixed-hardwood management planning.

Linear programming models form an integral part of advanced forest management planning models in the USDA Forest Service and some Australian state forestry services, even as concepts of forest planning have shifted from functional analysis to multidisciplinary and integrated forest management planning. Fiji forest management decision making can no longer rely on the old and inept planning process. The Forestry Department needs to develop and implement some scientific management techniques, taking advantage of advanced technology developed by the USDA Forest Service and in Australia.

1.1. Forest planning process - Fiji Forestry Department

The Fiji Forestry Department is not required by law to produce forest management plans for plantations under its jurisdiction, nor for native rainforests that it jointly supervises with the Native Land Trust Board (NLTB) for landowners. The forest planning process is at present too fragmented and inefficient to meet the industrial and environmental requirements entrusted upon the Forestry Department. Forest management decision making is too centralised, restrained by limited expertise in most forest disciplines, constrained by minimal budget, and suffers from undefined management priorities with unclarified goals.

The Forestry Department was formed in response to a specific problem, i.e., how to manage native rainforests to safeguard the fragile environment and meet the national forest product requirements (Bula, 1989). The forest management responsibility was distinctly custodial. Therefore, before any forest activity could be implemented on native land, "consents from landowners and approval of NLTB" have become the primary challenging factor. Given the complexity surrounding the forest resources and the responsibility and technical nature of forestry activities, the Forestry Department was seen as a competitive land user and viewed with scepticism since its inception in 1913. In recent years, every action it took, or did not take, prompted either public criticisms or landowners discontent, indicating that the Forestry Department is not effectively managing the problems at hand.

Surprisingly, the colonial system of "one-way communication" of forest policy and instructions from "top-to-bottom" had worked, resulting in the accomplishment of timber self-sufficiency in 1974 and the partial fulfilment of targeted reforestation program of grasslands (60,000 ha) and logged over rainforests (100,000 ha) (Fiji Govt., 1985). In the last five decades, the forest management was largely timber oriented, based on timber commitment to industries, and availability and accessibility of resources. Technically based decisions were scarce or cleverly disguised, as decisions were often individually or politically motivated and based on experiences from other countries.

A modified and rational approach to forest management is critical in Fiji, to assist decision making that could stabilise the fragile environment and economy (Drysdale, 1988; FD, 1988; Tuyll and Tuinivanua, 1988). The needed approach should promote multidisciplinary and integrated planning toward multiple-use management (Drysdale, 1988). Forest planning processes should take advantage of advanced technology, e.g., computerised technology and other mathematical programming techniques (linear programming models) as analytic tools to assist the decision making. An appropriate forest resource planning hierarchy could be portrayed as follows :

1. National Forest Planning :

To be realistic, National Forest Planning (NFP) must take into consideration the distinction between developed and developing countries and their different economic, political and social conditions. In particular, developing countries are generally more populous, poorer, and technically underdeveloped (Westoby, 1989). Realising these features, NFP must have, if possible a quantified concept of its future place in domestic and international markets and timber economy. The planning should have some notion of the extent to which it intends or expects the forest resources to contribute to timber and non-timber needs.

2. Divisional Forest Planning :

Divisional Planning (DP) would be responsible for translating forest policy and objectives into prescription plans. To achieve this, appropriate planning and analytic tools must be devised. Quite often, DP provides an essential link, ensuring efficient connection between management plan at the divisional and station levels to the National Plan. Examples of DP would include a production plan that defines the supply of wood to existing wood processing mills; recreation plan; and protection plan for water catchments, wildlife and other reserves.

Most importantly, Divisional level planning would not only decentralise responsibility of management planning but also enhance decision making for divisional and station managers. These plans should be flexible, accessible to all staff, practical and easily understood by users, and capable of analysing and producing realistic solutions.

1.2. Objectives of the Study

The prime objective of this study was to introduce advanced forest planning technology through the use of a computerised mathematical programming model, a powerful analytic tool that could assist in making wise and efficient decisions on modern forestry problems. The primary objective of this study is to :

1. Test and evaluate the feasibility of the SCHEDULER System as :

   (a) an appropriate harvest wood allocation system for the mixed-hardwood plantations of the Fiji Forestry Department.

   (b) a useful tool for advanced forest management planning process.

   (c) an efficient decision support system.

Given the primary is satisfied, success of the study would :

1. Create an awareness for advanced forest planning techniques, thus providing better insights into forest management problems and the required information technology for the system to produce quality results.

2. Replace the 'ad hoc' decision making based on haphazard planning and make scientific forest management techniques an integral part of planning processes.

3. Adopt a modified or transformed advanced technology : computerised mathematical programming techniques, e.g., LP models that coincide with the budget level, staff, quality and quantity data and the value of forest resources being analysed.

4. Intensify advanced forest management planning at all divisional and station levels.

The multi-stage objectives would not only strengthen the operational planning at the divisional and station managers levels but the resulting national plan. Quality planning at base levels would not only promote quality prescription plans but also efficient decision making for practical and flexible management planning.

Chapter 2

2. DEVELOPMENT OF FOREST PLANNING PROCESS IN OTHER COUNTRIES

2.1. Why the USDA FS and Australia ?

Fiji can no longer regard its forest economy a closed one. The country's self-reliance reached two decades ago, and now, the exportable surplus from the native forests and plantations has forced the national planners to develop ways that ensure the optimum economic utilisation of the forest resource. Yet, Fiji's forest management planning is at its juvenile stage. The reality is that, the Fiji forest management is technically backward and falls far behind its developed neighbours. Fiji needs to outwardly research their forestry development and planning to avoid flaws of the past and keep pace with the modern forestry development.

The USDA Forest Service and Australian State Forestry Services have made professional approaches to their forest management in the early and mid-1900's respectively. Interestingly enough, their forestry development have gone through similar changes from the single objective to the conflicting multiple-use management planning and the decision support system to optimise these objectives. The increasing and conflicting public demands on Fiji's forest resources are no different from that experienced in neighbouring countries. So, by gaining a better understanding of their systematic approach to solution method techniques would not only promote the introduction of advanced management planning techniques, but most importantly, enhance the problem solving by using an efficient decision support system.

2.2. United States Department of Agriculture-Forest Service (USDA FS)

After Congress passed the Organic Act of 1897 and Transfer Act of 1905, the USDA Forest Service was established as the governing agency of the National Forests. These are comprised of 191 million acres (77.3 million hectares) of forest land with annual estimated production of 12 million board feet of timber, 10 million animal unit months (AUM) of grazing, and many other products, such as recreation opportunities (Iverson and Alston, 1986). Over eight decades, the USDA Forest Service has evolved from custodial protection and conservation of these national forests to intensively integrated management at an unprecedented scale.

Forest planning is an ancient art. Germany had long been managing its forests on a sustainable basis. This had influenced the USDA Forest Service planning process as well as the underlying ideology (Alston, 1983). However, Gifford Pinchot, Chief of USDA Forest Service, 1898, not only spelled out the necessity of multiple-use planning, but also advocated "that forest conservation should include wise use and, when appropriate, protection from overuse as well as long term preservation of the productivity of forest reserves was to be implemented through planning" (Iverson and Alston, 1986). A professional approach to forest management, recognising the many uses of forests other than just timber production was the only alternative for managing the new Forest Service's 85.6 million acres (34.6 million ha.) of national forests in 1905 (Alston, 1983).

The concept of multiple-use was later broadened from the commodity use of forests to include outdoor recreation, wildlife habitat, environmental amenities and aesthetics (Alston, 1983). Similarly, planning emphasis also shifted from local and forest level to that of national issues. It called for more flexible multi-purpose management planning process that reflected not only the national economic conditions but also prepared for changes to cope with community stability and employment opportunities (Cameron, 1928).

The advent of World War II had tested the national forest management plans, proving them to be largely academic. These management plans were for resources that nobody wanted. Instead, their forest supply was drawn from the abundant old-growth timber of private, commercial and industrial forests at lower costs (Behan, 1967, 1981). Demands for forest produce for housing and construction work continued to soar, making the raw materials in the forest reserve a prime target. However, only 45% of forest area of the USDA Forest Service had been roughly surveyed and inventoried, with less than half the inventory data collected been analysed. The basic land classification scheme used for inventory and timber planning was questioned by studies of Wikstrom and Hutchison (1971), who showed the estimates were not complete, lacking important factors such as accessibility, difficulties of regeneration and soil stability measures.

The postwar period between 1945 and 1960 saw the reshaping of forest management planning in reaction to experiences that previous concepts were too academic. Gross (1950) commented that many of the formulas developed were highly theoretical. Nevertheless, they paved the way for timber activities and harvest schedules that could answer when, where, how and how much timber to cut and regenerate to achieve the management objectives. For example, Area and Volume Control methods were used to regulate the allowable cut. With Area Control, the emphasis was on an annual cut of equal area. Volume Control was focussed on providing an equal volume to harvest annually. The search for more flexible formula identified the Hanzlik's formula[1/] that was quite popular from 1920's, and well into the 1950's. The Hanzlik method was able to regulate the cut and to permit the rate of harvest to exceed growth where old growth virgin forests predominated. But the search continued, looking for better rotation length, best management practices and best alternative strategies.

1/ Annual cut = (Vm)/R + I
where R = rotation length for young growth stand
Vm = volume of merchantable (old growth) timber
I = forest growth(increment in immature stand)

The 1900 to 1950 era saw an end to custodial management of forest resources (Clawson, 1983), where protection and preservation of forest resources had to undergo inevitable changes towards intensive forest management. The 1960's and 1970's period marked the recovery of the housing and construction industry, accompanied by increase in demand for timber and other uses of forest resources. Favourable stumpage rates had boosted timber harvesting throughout the country, prompting public foresters to reveal a pessimistic view of timber famine. This pessimism was based on inadequate data. Reappraisal has indicated the estimated allowable cut was based on over-estimated, over-optimistic assumptions of the amount of growth on forested land being available and economically feasible to harvest (Duerr, 1960).

The pressure for increased harvest was accompanied by rising demands for other outputs and resources of the National Forests (Craft, 1970). The increasingly competitive users led to the introduction of the Multiple Use Sustained Yield (MU-SY) Act 1960, attempting to balance the demands and services on the Forest Reserves (Alston, 1972; Craft, 1970), and a series of studies on timber supply problems. However, it was the notion of "allowable cut effect" of Multiple Use Sustained Yield that became the focal point of debate (Bell et al., 1975; Teeguarden, 1973; Hyde, 1980). It led to the development of Timber Resource Economic Estimation System (TREES) which used a binary search algorithm to analyse the future timber availability in Oregon (Johnson and Tedder, 1983). Fight et al (1979) discounted the notion that the allowable cut effect was the main constraint, but found constraints on protecting water quality, recreation values, and wildlife habitats were so severe that they could vastly influence the timber program optimisation.

A linear programming model, Timber Resource Allocation Method (Timber RAM), developed by Navon and others (1971) was used to try to optimise the allowable cut. Timber RAM has been used to provide the functional plans for timber management which were integrated with plans for other functional areas into the multiple-use plans (Chappelle et al., 1976; Iverson and Alston, 1986). The desire was to construct models that could look beyond the current rotation and also provide estimates of expected harvest and growth relationships to the future. It required more detail information, not only of resources but also activities to be applied. The attempt was faced with two problems: estimation of existing inventory and its growth and yield models and secondly, translation of information into an allowable cut estimate. With the sophisticated computer models in use, the USDA Forest Service continued its timber scheduling beyond the current rotation but were restricted as resource interactions could not be modeled effectively. This was important as the MU-SY Act 1960, the National Environmental Protection Act (NEPA) 1969, and the National Forest Management Act (NRMA) - 1976, were emphasising a shift from single objective to multidisciplinary and interdisciplinary planning (Iverson and Alston, 1986).

With the advent of computer technology, computer based analysis was developed by various agencies to handle national and regional level planning (Field, 1973; Bell, 1975; Bell et al, 1975). For example, four models under the National Interregional Multi-Resource Use Model (NIMRUM) were developed, following the Renewable Resource Planning Act (RPA) - 1974, to minimise operational costs of alternative national programs, using linear programming in the system constrained by timber harvesting practices, domestic grazing, range practices and wildlife practices. Others include a model evaluating employment and income generated by the programs, a Future Forgone model accounting future options lost and its impact on citizens and lastly, a Social Conflict model which tried to quantify the extent and direction of these programs (Alston and Freeman, 1975). It was realised from the computer models that they were too expensive and the "top - bottom" approach had great difficulties in linking to site - specific multi-resource forest planning. To improve the situation a "bottom - up" approach was needed. Secondly, a meaningful approach would only be achieved through integrated and interdisciplinary planning, turning away from the Forest Service product oriented concept followed by the strengthening of local or regional level planning. In other words, the shift in the mode of planning was made toward decentralising the forest management planning process.

With the MU-SY Act of 1960, emphasis shifted toward a balanced approach in the use and management of forests and range lands (Alston, 1972). Nevertheless, no matter how far the intention was to recognise the balanced approach, the absence of adequate data and expertise in non-timber planning had resulted in multiple-use plans that were still largely timber oriented (Schweitzer and Cortner, 1984).

In response to the National Environmental Policy Act (NEPA) - 1969, requiring all agencies to prepare Environmental Impact Statement (EIS), the USDA FS restructured its system of forest planning. Each forest is divided into subareas of forest called "units," encompassing forest zones, watershed, recreation, streamlines, wildlife habitats and other critical zones. The multiple-use plan would be prepared for all forest components, giving interdisciplinary and / or integrated plans of national forests. However, the functional plan would continue to supplement the overall decision concerning forest resource management. National level planning was becoming the main concern of the general Forest Service planning effort. For example, national level analysis would determine the form and extent of budget allocations to National Forests and Regions.

Among computerised analysis systems used in forest level and unit planning was the Resource Capability System (RCS) which simulates water quality and water quantity as an alternative approach to timber scheduling models (Johnson, 1986). The perception of the RCS and its refined version Resource Allocation Analysis system (RAA), biased toward hydrological concerns and the Timber RAM and Multiple Use Sustained Yield Calculation Technique (MUSYC) being largely timber oriented caused confusion among forest planners.

Eventually, this lead to the formulation of the FORest PLANning Model (FORPLAN), a primary analysis tool providing a link between functional resource planning and integrated land-use planning (Kelly et al., 1986; Johnson, 1986). FORPLAN was comprehended as an analytic tool for developing forest ecosystem management plans or capable of accommodating both land and water in the forests, a role that Timber RAM and MUSYC could not fully handle. Refinement of FORPLAN in Version 2 enabled each discipline to be redefined as a focal point, giving each discipline equal opportunity.

Like most former models and its predecessors, FORPLAN uses a mathematical programming technique especially linear programming, classifying it as linear model. FORPLAN intends to overcome the short comings of previous models, but certain criticisms are leveled at its inability to handle non-linear problems. The extent of the model can be very complex and sophisticated to provide a clear insight into the planning process. However, mathematical programming such as linear programming, provides a useful mechanism in understanding the nature of the problems.

2.3. Australian States Forest Planning.

The extent and type of forest planning varies between States and is largely determined by the data required and available. For example, data from natural hardwood forests are scarce and because of its slow growth and low value, detailed planning and modeling is limited (Australian Forestry Council, 1987). On the other hand, Australia had over a century of experience with industrial plantations of fast growing, exotic species like *Pinus radiata*. The extensive inventory and growth and yield data collected over the years, enabled the formulation of simulation models and optimisation.

The analytic tools used in plantation management vary widely between States, e.g., graphical methods - South Australia (Lewis et al., 1976); linear regression - Victoria

(Turner et al., 1977), - South Australia (Ferguson et al., 1978); STANDSIM- general model for simulating growth of even-aged stands - Victoria (Opie 1972). Simulation models of growth and yield saw the move to more advanced form of analysis, e.g., using linear regression with computer modeling replacing graphical analysis. Simulations for cutting plans and yield regulations schedule the types of thinning operations and clearfelling for 1 - 5 years and yield regulations for 20 - 60 years. These simulation models are product oriented to satisfy the industries. The objectives behind these models were ease of use, cost effectiveness and ability to take advantage of computer technology. Examples of cutting plans include: Plantation Simulation Model 1 (PSM) - Cutting Plan, using stand growth model -Victoria (Dargavel et al., 1976); PSM 2 - Cutting Plan, using linear regression - South Australia (Lewis et al., 1976); PSM 4 - Yield Regulation, using yield table projection - Victoria (Dargavel, 1969); PSM 5 - Yield Regulation, yield table projection - South Australia (Lewis et al., 1976); PSM 7 - Yield Regulation - FORSIM, growth simulation based on basal area, height and simulation of harvesting operation - Victoria (Gibson et al., 1971). The extent and complexity of models vary considerably depending on variation of sites and the decision used for selection (Australian Forestry Council, 1978). A common weakness of the simulation models had been the limited range of management strategies as the complexity of models increased (Lewis et al., 1976; Dargavel, 1969)

The optimisation models for yield regulation represent the introduction of the linear programming model into forest management planning. Linear Programming models developed by Ware et al (1971), and Johnson and Scheurman (1977), provided the software packages for analysis. Optimisation models that were developed include : the RADiata Harvesting OPeration (RADHOP) - NSW (Brack, 1988) ; and MASH for the modeling of *Eucalyptus regnans* and *E. delegatensis* regrowths - Victoria (Weir, 1972). It was realised that the models required extensive data, were too expensive to develop and operate, and needing specialised trained staff. However, it provided an appreciation and insight into interactions between alternatives being modeled.

A balanced approach to multiple use management and integrated planning of native hardwood forests was pursued in Australia, especially in Victoria (Victorian Govt., 1986). Growing confrontations between practitioners of forest management and environmentalists had intensified over the years (Church, 1987). Similarities in the problem scenario between the United States and Australia has instigated the Otway Project using FORPLAN (Dargavel and Turner, 1989; Duguid et al., 1990). In the Victorian context, the Otway model is to resolve some forest management problems, viz.:

(1) how to set the level of the various commitments such as timber production and water supply.

(2) how to manage the forests to meet these commitments

(3) how to ensure that all other uses and values of the forest such as recreation and conservation can be sustained (Duguid et al., 1990)

The development of FORPLAN for the Otway Project can assist the decision making process of the Department of Conservation and Environment of Victorian Government in many ways including :

(1) providing a clear presentation of the planning problem

(2) highlighting missing information during the process of development

(3) testing of flexibility by applying ranges of management alternatives

(4) analysis of responses to different management alternatives

(5) examination of conflicting interactions between multiple uses

(6) quantification of the impacts of management alternatives

(7) modification of guidelines for management to improve outputs :

- specification of goods, services and values for the plan period

- prescriptions to produce goods, services and benefits for the plan period

(8) highlighting poorly defined information critical to good management for further inventory or research (Duguid and Dargavel, 1988)

Although FORPLAN provides potential advances in modern planning model, its many deficiencies are yet to be overcome to become user friendly.

2.4. Linear Programming Models as Analytic Tools

The above review suggests the evolution of the planning process from the functional analysis of Timber RAM to a multidisciplinary and integrated planning method using FORPLAN. Linear Programming is a mathematical programming technique that provides the mechanism to schedule specific management activities of alternative management strategies. It enables the comparison of alternative management strategies to achieve stated goals within limitations of resource.

Decision variables of models are associated with activities representing prescriptions for land use on a specific area of land. In the evaluation process, according to specific criteria defining terms of constraints and objective function, the Linear Programming (LP) model has the ability to select decision variables that optimise (maximise or minimise) the objective function that satisfies the set of constraints. The feasible area of LP model is constrained within bounds of activity columns and constraint rows. The objective function then guides the LP model within the feasible area to a solution that efficiently assigns the land area to appropriate land use strategies. The availability of alternative solutions (duality) provided by the LP model also portrayed important information, e.g., for sensitivity analysis techniques.LP models developed with computer technology have encouraged model developers to take advantage of its analytic ability and gain insights to interactions between alternative management strategies. LP problems are simply abstractions from the realities of on ground management, therefore, a clear understanding of model specification and user interaction forms an indispensable part of the process (Iverson and Alston, 1986).

Chapter 3

3. DEVELOPMENT OF MATHEMATICAL PROGRAMMING FOR FOREST MANAGEMENT PLANNING

3.1. The Emergence of Mathematical Programming

Management Science or Operations Research is a hybrid science with origins ranging from mathematics, physics, statistics, economics and other applied sciences (Thompson, 1967). Giving a precise definition of Management Science may be rather difficult, which is not surprising, because it is simply what management scientists do (Dykstra, 1984). For convenience, Wagner (1969) defined Management Science as :

" **A scientific approach to problem solving for executive management**"

by using Management Science applications involving :

- **"constructing mathematical, economical and statistical descriptions or models of decisions to treat situations of complexity and uncertainty.**
- **analysing the relationships that determine the probable consequences of decision choices.**
- **devising appropriate measures of effectiveness to evaluate the relative merits of alternative actions"**

Management Science is concerned with scientific management, or in other words, the applications of scientific methods to management of organisations or systems (Dykstra, 1984). Management Science was developed during World War II to study and develop solution methods, and how efficient decisions could be reached. In studying solution methods, the importance of model building was a matter that could not be overlooked. Model building requires the specialised skills of model developers. As a result, most of the models that have been devised were largely tailor-made for specific uses. In Management Science, a model is always mathematical by nature, an abstraction of a real management problem (Wagner, 1969). It must have sufficient detailed information to provide a solution that is realistic. Reaching a realistic solution is not an easy task, thus making model building difficult and strenuous work for model developers.

Mathematical Programming is a subdiscipline of Management Science (Dantzig, 1963; Dykstra, 1984). It represents a class of mathematical techniques that, from time to time, proved to be a powerful and effective approach to solving real management problems (Hall, 1967). To optimise (maximise or minimise) the value of a stated objective under a set of constraints, mathematical programming is set to follow a defined procedure called an " algorithm." A successful algorithm improves and reduces the number of iterations while ensuring that the optimal solution is not overlooked. The most developed of these techniques is linear programming. Despite its wide use, linear programming models have their limitations. Other techniques that were developed because of the inability of linear programming models to handle other management problems include : integer, quadratic and dynamic programming.

Mathematical programming in most contexts is concerned with the optimal allocation of scarce resources to competitive users. Multidisciplinary and integrated planning have been recognised as potential means of assisting decisions on conflicting demands and values on forest resources. The efforts to use mathematical programming in real scheduling problems highlighted some unresolved difficulties of the LP model. But the mathematical programming techniques have provided greater insights into real management problems, in particular, the social, economical and biological issues(Ware and Clutter, 1971; Hall, 1967; Dykstra, 1984).

The departure of the planning process from the concept of traditionally regulated (normal forest) forests was inevitable, especially with its inflexibility and inability to utilise management information pertinent to current conditions, and to consider management alternatives being made available by mathematical programming techniques. With mathematical programming modeling it was possible to evaluate a wide range of resource allocations and scheduling that was never thought possible (Wagner, 1969). In particular, linear programming provided a breakthrough in amplifying the analytic ability of management to decide the best alternative (Wagner, 1969; Ware and Clutter, 1971; Johnson and Tedder, 1983).

3.2 Single Objective Approach of Forest Management Planning

3.2.1. Development of Linear Programming Technique

Linear Programming is a discipline of Management Science which uses mathematical programming techniques. Linear Programming (LP) has a number of origins : Game Theory ; Input-output Analysis ; and the Transport Problem . Dantzig (1947) developed the Linear Programming approach to solving scientific management problems. Linear programming is widely accepted as a scheduling and assignment technique. It optimises (maximises or minimises) the allocation of resources according to a stated linear objective function by satisfying a set of linear constraints.

Curtis (1962) described how LP was perceived and defined by some scientists :

(1) **"Linear Programming is a technique for specifying how to use limited resource or capacities of a business to obtain a particular objective such as least cost, highest margin or least time, when those resources have alternative uses. It is a technique that systemises for certain conditions the process for selecting the most desirable course of action from a number of available courses of action, thereby giving management information for making a more effective decision about the resources under its control"**

(2) **"Linear Programming is concerned with the problem of planning a complex of interdependent activities in the best possible optimal fashion"**

Linear Programming represents a quantitative analysis of management problems. A prelude to a quantitative analysis requires a thorough understanding of the decision problem (see Study Area and Case Study). Having a preliminary notion of : principal management decisions and measure of effectiveness of choices (objectives); marginal usage of each resource (constraints); and comparisons of alternatives (sensitivity analysis) are prerequisites that pave the way for a better appreciation of the problem and decisions to be made (Wagner, 1969; Dantzig,1963). To be classified under LP, a number of assumptions must be satisfied. These assumptions delineate the limits of LP, making it computationally possible to achieve a better insight within the decision problem:

1. Linearity :

Essentially, the objective function and constraints have to be linear throughout the process of each activity. For example, all constraints must remain as first - degree polynomials. Strictly speaking, all variables must have exponents of 1. Assumptions of linearity appear more restrictive than they are in actual use in the processing of each activity.

2. Proportionality :

It requires that the quantity of flow of various items into and out of the activity is always proportional. For example, to double mill volume intake would mean doubling of the number of haulage trips.

3. Non-negativity :

An activity can only operate with positive numbers or quantity. Negative numbers or quantities of activities are neither possible nor workable under this condition.

4. Additivity / Divisibility :

Assumptions of additivity and divisibility imply that the LP model is formulated under terms of linear relations. Each variable can assume any real value, integer or continuous.

Formulating a LP model requires an understanding of the decision problem that provides information input under these fundamental stages :

1. Objective :

An objective represents the desire of the decision maker. It optimises one aspect of the decision problem. For example, a forest management goal may be to maximise the utility of forest resource in profits (measured in present net value (PNV), return on investment or maximum wood flow). Other non profit objectives including minimising cost and maximising the timber volume production.

2. Goals and Constraints :

A goal is a mathematical function of decision variables. Unlike an objective function, a goal represents a combination of objectives with a target value, and with a certain degree of flexibility. A constraint, on the other hand, is in every way like a goal but is quite inflexible and absolute. However, if a goal is to be satisfied then it becomes a rigid constraint or an absolute goal. Differences between goals and constraints are very subtle. Under a strict mathematical notion of a constraint, a right hand side value must be satisfied. Violating this constraint could simply result in an infeasible solution. A goal bears no significance to single objective mathematical programming but has an important role in multiple objectives approaches. Common forms of goals and constraints include : maximum mill requirements, maximum area and volume of wood flow, budget, or labour supply.

Given its pragmatic considerations, current management decisions should not be restricted by long term objectives. Uncertainty in wood requirements, prices, costs, markets and technology can change future scenarios. Therefore a proper basis for the management of a profit oriented enterprise is to optimise (maximise) its present net value subject to constraining environmental factors. For non profit oriented management, achievements of balanced use may prove more complex to formulate and implement.

3. Problem Formulation :

The establishment of a baseline mathematical model is a key part of the first phase of model formulation (Wagner, 1969; Ignizio, 1982).

Model Formulation

The attempt to identify and mathematically define decision or control variables, objectives, goals and constraints that best describe the decision problem can take the following basic steps:

1. Determination of Decision (Control) Variables

The decision variables are those variables that we can actually control, sometimes referred to as control variables.

2. Formulation of Objectives and Goals

The objectives and goals can be determined by looking at the followings:

- Aspirations (desires) of decision makers
- State of resources (limiting)
- Any other explicit or implicit restrictions placed on the choice of variables

The distinction among objectives and goals in the context of the problem formulation can be defined as follows :

(a) Objectives are represented by mathematical functions of the decision variables, expressing the desires of the decision maker such as maximising PNV or minimising cost. In linear form, the objective function is linear with the right hand side of the objective function left unspecified.

$$\text{maximise } f(x) \quad \text{or minimise } f(x)$$

(b) A Goal is a mathematical function of the decision variables that represent the combination of the objective and a target value.

$$f(x) \ \geq, \leq, \text{or} = b.$$

A linear programming problem can be written in a number of ways. For example, the objective function may be maximised or minimised, constraints may be in either direction of inequalities ($\geq$ or $\leq$) and equality (=).

Objective :

$$\textbf{Max. (Min.)} = c_1 x_1 + c_2 x_2 + \ldots\ldots\ldots\ldots + c_n x_n$$

where

$c_1, \ldots\ldots, c_n$ are constant parameters. Each parameter c_j measures the contribution of corresponding variable x_j to the objective function

Goal or Rigid Constraints :

Subject to :

$$a_{1,1} x_1 + a_{1,2} x_2 + \ldots\ldots\ldots\ldots\ldots + a_{1,n} x_n \quad (*)\ b_1$$

$$a_{2,1} x_1 + a_{2,2} x_2 + \ldots\ldots\ldots\ldots\ldots + a_{2,n} x_n \quad (*)\ b_2$$

$$a_{m,1}\, x_1 + a_{m2,2} x_2 + \ldots\ldots\ldots\ldots\ldots + a_{m,n} x_n \qquad (*)\ b_m$$

where $\quad x \geq 0$

and $b_1, b_2, \ldots\ldots\ldots, b_m$ are constants. It measures the amount of resources available, e.g., area, budget, etc., and the expression (*) is either type I inequality ($\leq$) or a type II inequality ($\geq$) or an equality for each $1, \ldots\ldots, m$. Therefore a $_{i,j}$ is a constant that measures how much of resource 'i' is used per unit of activity x_j. For example, product $a_{i,j}$ is the amount of resource 'i' used when activity 'j' is at level x_j. Addition of these products (activities) leads to the general expression for total amount of resource 'i' used by 'n' activities. The standard form can be written in somewhat more compact form given : x_j ($j = 1, \ldots\ldots, n$).

Objective function :

$$\textbf{Max. Z} \quad = \quad \sum_{j=1}^{n} c_j\ x_j$$

Constraints :

subject to

$$\sum_{j=1}^{n} a_{i,j}\ x_j \quad \leq \quad b_i \quad \text{for } i = 1, \ldots\ldots, m.$$

$$x_j \quad \geq \quad 0 \quad \text{for } j = 1, \ldots\ldots, n.$$

Solving Linear Programming Problems

A LP problem can be solved by a number of solution techniques. For example, a graphical method may be used, but it is only limited to small size problems. A process commonly used to solve LP problems involves a string of the same calculations repeated over and over again called an "algorithm." This particular algorithm for solving LP problems is called the "Simplex Method."

Simplex Method

Dantzig (1963) developed the Simplex Method in 1947. It's an algorithm for computing numerical solutions to linear programming problems. So, after decades of computational experience, Dantzig became convinced that the Simplex Method was an "efficient" algorithm , meaning that it could quickly find the optimal solution to a LP problem irrespective of problem size. In other words, the simplex algorithm can determine the optimal solution by evaluating only a fraction of the total number of basic solutions.

Slack variables

In solving LP problems via the simplex algorithm, it is essential that type I and II inequalities are converted to equalities in the linear equations. The conversion of inequalities into equality linear equations requires the addition of non-negative variables to the left hand side called slack variables. The slack variables represent a measure of the amount of slack or unused resources in the constraints. For example, if in a constraint row involving x_1 and x_2, the value of x_3 (slack variable) = 0, then there is no slack in the constraint. If on the other hand, the added value of x_1 and x_2 is less than the right hand side value, x_3 (slack variable) represents the difference in value.

Basic solutions

The concept of the basic solution is fundamental to the development and understanding of LP (Ignizio, 1982). In LP problems, there are only a finite number of solutions which need to be considered in order to find the optimal solution, if one exist (Dykstra, 1984). The optimal solution will always occur on the boundary of the feasible region, in particular, at an extreme point, i.e., where two or more constraint boundaries intersect. These extreme points are known as basic solutions.

One method of finding the optimal solution to the LP problem is to solve for all possible basic solutions. Then select the basic solutions that satisfy all the constraints and the non-negativity conditions. Of these basic feasible solutions, the optimal solution is selected, representing the maximum and minimum values of the objective function.

Duality

The concept of duality is quite important in linear programming because it provides the basis for sensitivity analysis (Dykstra, 1984). The symmetrical formulation (Dual) is very useful in the interpretation of the solution, especially in testing how the objective function changes as one constraint changes while others remain constant (Buongiorno et al., 1987)

To every primal there is an opposing dual. They are related in such a manner that the optimal solution of the primal provides all the information needed to determine the optimal solution of the dual. Formulation of duality is somewhat straight forward but the mechanics differ according to the form of primal. For example, the canonical form of a LP is one where :

primal - objective function is maximising
- all constraints are of type I inequalities ($\leq$)
- all variables are restricted to non-negative values

and dual - objective function is minimising
- constraints are of type II inequalities ($\geq$)
- all variables are non-negative values

Sensitivity Analysis

Sensitivity Analysis refers to an analysis of the effects on the optimal solutions of LP problems of changes in input-output coefficients, cost coefficients and constant terms. For example, any change in an objective function coefficient could make a difference between an unbounded solution and a finite optimal solution. Unlike infeasible solutions that result from an over restriction of the feasible region, unbounded solutions arise when the value of the objective function can be arbitrarily large (assuming maximisation) but the solution remains feasible.

Changes in the optimal solution can also be investigated by the systematic shift in values of constraints (right hand side parameters). An increase with all other conditions of the problem remaining constant would cause the boundary to shift outward by relaxing the constraint boundary. It would induce a marginal change in the objective function relative to changes (increase / decrease) in the decision variables. The amount by which the objective function changes in response to unit change in the constraint is known as the "shadow price", imputed value or marginal cost of constraints. The shadow price of any nonbinding constraint is always zero. In a graphical solution, a nonbinding constraint does not pass through the optimal solution. In other words, nonbinding is a redundant constraint but a nonbinding constraint is not necessarily ~~a~~ redundant. A nonbinding constraint, although changing the boundary of the feasible region, has no effect on the optimal value of objective function.

3.2.2. Scientific Forest Management Approach using Linear Programming

Period - 1950s - 1960s :

Curtis (1962) showed how LP models can assist forest management in 'forest compartment scheduling.' The decision problem was based on a policy statement requiring a fixed area to be regenerated annually. LP was used in allocating clearfelling proportionally in order to provide an even distribution of age classes, while at the same time maximising rate of return and minimising costs. A general LP model used by Curtis (1962) can be defined as follows :

$$\text{Max } T = \sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij} \quad X_{ij}$$

subject to

$$\sum_{i=1}^{n} X_{ij} = Y_i$$

$$\sum_{j=1}^{m} X_{ij} = A_i$$

$$X_{ij} \geq 0$$

where :

i	=	compt. (i = 1,........, n)
j	=	period (j = 1,........, m)
T	=	Total harvest or Max PNV
C_{ij}	=	total wood harvested from cutting compt. 'i' in year 'j'
X_{ij}	=	plantable acreage to be cut in year 'j' from compt. 'i'
Y_i	=	plantable acre required to be cut in year 'j'
A_i	=	plantable acre in compt. 'i'

In a similar situation, Kidd, et al. (1966), derived a schedule of timber harvest over time that would maximise present net value. The forest regulation problem was constrained by area, age distribution of resource and management limitations as wood flow, labour and budget. On the same token, LP techniques have been used to determine an economical optimum pattern of converting an irregular forest to sustained yield while maximising PNV (Nautiyal and Pearse, 1966).

Although LP models had been widely accepted in forest management planning in the 1960s, it was restrictive in temporal scheduling, reducing its application to single rotation models. Hall (1967) also had difficulty with continuous variables of LP output solution, in particular, in the treatment of fractional blocks, e.g., homogeneous but disconnected blocks. Other limitations include the task of making realistic management problems compatible to computers. Computer limitations included computerised program running time which was far too long and too costly. However, LP models have been used to maximise PNV by harvest scheduling under certain policy statements. Loucks (1964) on the other hand, use LP model to maximise volume to be cut (Cut- Schedule) and minimise area to be harvested for sustained yield management.

Given the working capability of LP models it was important that all 'information input' : yields, costs, prices, etc., be quantified (Kidd, et al., 1966 ; Curtis, 1962). Improvements of information systems and data bases have proven to be one way of ensuring reliable solutions. Management information including resource inventory data : forest areas, harvest units or compartments, species, volume,and product assortments are important variables. Hall (1967) recognised LP models as useful planning and management decision making tools.

An approach to a large scale forest scheduling problem using LP decomposition was developed by Liittschwager and Tcheng (1967). The model was to maximise wood production over 25 years by solving a series of smaller manageable problems rather than a large problem. The procedure catered for limited computer capacity. Linear programming models have great potentials in cutting, planting and other silvicultural operations. However, limitations of LP are there to stay and must be considered in the management decision making.

- **Period 1970s :**

Conceptually, managing industrial forests to maximise PNV, cash flow or maximise rate of return have placed profit oriented enterprises under a common denominator, i.e., efficient allocation of factors of production : labour, capital and scheduling of harvesting operations (Ware and Clutter, 1971). Ware and Clutter (1971) subdivided their problem formulation into two computational phases : an "appraisal phase", delineating the temporal cutting patterns for each cutting unit ; and a "scheduling phase", using LP model to assign cutting units to maximise PNV. Cutting regimes that provide the maximum PNV seldom provides a stable wood flow pattern. Therefore, readjustments of some suboptimal harvest schedules are necessary and constitute the core of the cut-scheduling problem.

The Cut-Schedule model was constrained by :

- upper 'c_j 'and lower 'b_j' cordwood production.
- upper 'f_j' and lower 'e_j' area regenerated.

and defined by :

- period j (j = 1, ..., n)
- regime k (k =1, ..., m)
- cutting unit i (i = 1, ..., s)

Cut - Schedule model :

$$\textbf{Max PNV} = \sum_{i=1}^{s} \sum_{k=1}^{m} X_{ik} \, D_{ik}$$

subject to

$$\sum_{i=1}^{s} \sum_{k=1}^{m} Z_{ijk} \, X_{ik} \geq e_j \qquad (1)$$

$$\sum_{i=1}^{s} \sum_{k=1}^{m} Y_{ijk} \; X_{ik} \geq b_j \qquad (2)$$

$$\sum_{i=1}^{s} \sum_{k=1}^{m} Z_{ijk} \; X_{ik} \leq f_j \qquad (3)$$

$$\sum_{i=1}^{s} \sum_{k=1}^{m} Y_{ijk} \; X_{ik} \leq c_j \qquad (4)$$

$$\sum_{k=1}^{m} X_{ik} = 1 \qquad (5)$$

$$X_{ik} \geq 0 \qquad (6)$$

where

Y_{ijk} = yield of cutting unit 'i' in period 'j' under management regime 'k'

X_{ik} = proportion of cutting unit 'i' assigned to management regime 'k'

D_{ik} = total present value of cutting unit 'i' if assigned to management regime 'k'

Z_{ijk} = acreage of cutting unit 'i' regenerated in period 'j' under management regime 'k'

The listed constraints can be expressed as :

(1) & (3) = restriction imposed on per period regeneration acreage

(2) & (4) = restriction regarding periodic yield

(5) = cutting unit harvested under all regime must sum to 1.

(6) = non-negativity proportion of cutting units.

Result from use of the Cut-Schedule model showed that it was essential to contain "the size of area processed" to a workable size 20,000 - 60,000 acres (8,094 - 24,282 ha). Specification of planning period can be reduced to 1.5 - 2 rotations, i.e., 40 - 60 years of 4 - 5 years cutting length period, or 15 - 20 years planning period for short term wood flow and 1 - 2 years cutting period. Choice of interest rates is important as optimum schedule is quite sensitive to specified value of interest rate.

Navon et al (1971) developed the Timber Resource Allocation Method (Timber RAM), using past experience to formulate " plans which are efficient with respect to stumpage harvested, costs, or revenues and which are consistent with specified management policies and available resources" (Iverson and Alston, 1986). Timber RAM was developed to answer quite a number of management questions, in particular, that which relates to sustainable harvest level : "how much and where to cut". Timber RAM's analysis areas are divided into "timber classes" that have similar economical and silvicultural attributes. This approach is called "strata based" (Iverson and Alston, 1986). The planning period ranges from 120 - 300 years, with prescriptions of silvicultural treatments spanning through decades. Specified prescriptions include existing and yet to be managed timber stands. Initially, Timber RAM's harvest schedule was not controllable by "land classes". In 1972, US legislation of land categorisation was implemented to subdivide land into standard, special, and marginal components. By 1972, the reduction in harvest volume implied a revision of Timber RAM. Other non-timber competitive users were considered : recreation, range and wildlife. The change contradicts the original basis of Timber RAM, as a timber management planning model. The output solutions were typically timber oriented, causing dissatisfaction among non-timber planners in a multidisciplinary and integrated planning approach (Iverson and Alston, 1986). The shift from growth maximising formulas to a site-specific management approach or multiple-use modeling was far too complex for Timber RAM to handle (Iverson and Alston, 1986; Chappelle, et al., 1976).

The Multiple Use - Sustained Yield Calculation Technique (MUSYC) was developed by Johnson and others (1976), to handle what basically Timber RAM could not efficiently resolve (Iverson and Alston, 1986). Johnson and Scheurman (1977) introduced two models (I and II) of which Model I had been widely used in the Timber RAM (Dykstra, 1984). The key distinction between the two models lies in the definition of the decision variables. While Model I decision variables maintain the prescriptive managerial activities throughout the planning horizon on the existing stand, Model II produces two or more sets of decision variables. For example, one set of decision variables traces the actions on the existing stand, the second and other sets of decision variables trace the actions each time a stand is reestablished and harvested. Differences between Model I and II became apparent at the level of computational efficiency (Johnson, 1977). Model I was sensitive to minimum rotation age while Model II was sensitive to number of acreage groupings at each age that must be maintained for future stands (to be managed) within each type site.

Johnson's Model I formulation was used in MUSYC. However, the model (MUSYC) could handle the multiple-use considerations such as non timber uses of the forest only in the form of constraints on the timber harvestable from the various site classes (Iverson and Alston, 1986). In other words, the MUSYC prescriptions continued to be largely timber oriented. Improvement in constraints specifications helped in projecting more realistic harvest schedules. Geographically defined analysis areas were far more informative and useful than the strata-based areas of Timber RAM. Despite improvements in MUSYC to address the temporal dimensions of the timber management problems, it gradually came into disuse. A step into interdisciplinary planning towards a site-specific approach (unit planning) was a formidable challenge (Iverson and Alston, 1986).

The 1970s scheduling models , though quite advanced in their information systems and data bases, proved inefficient in meeting social and environmental demands. The changing phases of planning participants, i.e., to multidisciplinary and integrated planning have contributed significantly to the increasing diversity of planning models and objectives the managers have to optimise.

Period 1980s :

Johnson (1986) continued their pursuit to bridge the gap between functional resource planning and integrated land use planning by developing FORest PLANning (FORPLAN). It was designed to accommodate all lands and water in the forest area. Its decision variable role was enlarged not only to accommodate timber through time but multiple resource activities through time. These package activities or prescriptions represent an integrated set of activities, outputs, costs and benefits through the sequence of the planning horizon (Iverson and Alston, 1986). FORPLAN was developed with a new concept that separates "decision variables related to land allocation from decision variables related to activity scheduling." These can be related however by a process called "aggregate emphasis." An aggregate emphasis prescription enables management directives or policy statements (site-specific land use) to be tested over a composite of analysis areas in a user-defined zone. It delimits the set of prescription choices to be applied in both broader allocation of land or narrower assignment of prescription treatments to the land. Individual prescription assignment is made within the aggregate emphasis. In fact, it's a choice within choice.

The notion of activity scheduling for multiple resource production and that of land allocation are significant milestones set by FORPLAN. Other improvements accomplished by FORPLAN include :

- movement away from timber supply estimates based solely on strata-based analysis

- ability to user-constrain output flows, i.e., to set constraint across subsets of lands, activities and periods.

- provide better estimates of what would be available (i.e., timber, etc.) where and when but not how much (Iverson and Alston, 1986).

FORPLAN like its predecessors has its problems and criticisms. Running of the model has proven to be time consuming and expensive. Model size is a problem especially with stratifications reaching 250 - 800 analysis areas or more. Continued work on these problems, limitations and weakness led to the development of FORPLAN Version 2. Unfortunately, criticisms of Version 1 seem to have found their way to Version 2, but are application specific. An important finding was the shift in public criticism. While FORPLAN provides a unique forest planning tool and an improvement in the analysis of functional concerns, the integrated planning process has become the focal point of criticism.

Forest planning using LP for long term management planning is gradually finding its way to countries intending to manage its forests wisely, in particular , highly exploited forests of developing countries. For example, Kowero and Dykstra (1988) designed a reduced model of the "Model I" formulation of Johnson and Scheurman (1977) to "maximise the productivity of the forest estates and utilise the forest produce to the best advantage of the community" for Tanzania, on the east coast of Africa.

3.3. Multiple Objective Approach of Forest Management Planning

3.3.1. Goal Programming

Goal Programming (GP) is a modification of conventional Linear Programming (LP). Whilst LP models attempt to optimise allocation of scarce resources to satisfy one objective, GP in a similar format, considers several management objectives (goals) simultaneously (Field, 1973). Both procedures are constrained optimisations with similar assumptions : divisibility, linearity and non-negativity. However, GP requires explicit specifications of quantitative goals and any preference structure that may be associated with the objectives (Field, 1973). It's this property that differentiates GP from LP and makes it more flexible to overcome certain weakness of ordinary LP.

Goal programming is a mathematical programming technique for determining a plan of action offering a minimum aggregate deviation from a set of quantitative goals (Field, 1973; Dykstra, 1984). In fact, GP is a variation of LP (Field et al., 1980). A generalised GP methodology represents a modification of LP so that it can effectively be used for a multiple-objective approach. Although there are other approaches to multiple-objective problems, the GP method is noted for its flexibility, efficiency, ease of use and implementation (Ignizio, 1982). Goal programming has three basic approaches that form the basis of multiple-objective techniques : weighting or utility methods (cardinal or ordinal weighting) ; ranking or prioritizing methods (preemptive priorities). Beside these philosophical approaches, the basic thrust is to transform a multiple-objective model into a single-objective model (Ignizio, 1982). These approaches represent some of the extremes in multiple-objectives. To develop any robust and practical multiple-objective approach, certain relaxation of strict approaches or a compromise working combination of these approaches is necessary.

Although LP has gained wide acceptance, GP can complement its solution (Field, et al., 1980). In GP, goals are approached as closely as possible but need not all be met completely (Field, 1973). In contrast, LP requires the optimisation of a single dimensional criterion. So, when several activities are to be optimised, the LP solution output must be expressed in a common unit. This creates serious problems involving incommensurable values and difficulties in specifying relationships between activities in LP problems (Kao and Brodie, 1979; Ignizio, 1982). Goal programming, on the other hand, not only enables the simultaneous consideration of allocating activities whose outcomes are commensurable but also permits specification of activities whose levels cannot be associated in a common unit (Field, 1973).

Goal Programming Model Formulation

To mathematically transform an objective into goal with a goal programming framework one has to consider the objective function expressed in a linear form as shown by Field (1973) and Ignizio (1982) :

$$f_i(x) \quad = \quad f\,(x_1,\ x_2,\ x_3,\ \ldots\ldots\ldots,\ x_n) \quad =,<,> \quad b$$

where

$f_i(x)$ = objective 'i' as a function of decision variables $x = (x_1, x_2, \ldots, x_n)$

b = a quantitative objective

- there are three possible forms :

Goal type	GP form		Deviation variable to be minimised
(1) $f_i(x) \leq b_i$	$f_i(x) + d^- - d^+$	$= b_i$	d^+
(2) $f_i(x) \geq b_i$	$f_i(x) + d^- - d^+$	$= b_i$	d^-
(3) $f_i(x) = b_i$	$f_i(x) + d^- - d^+$	$= b_i$	d^+ & d^-

Field (1973) showed an interpretation of Ijiri's (1965) goal programming model as:

Objective :

$$\text{Min } Z \quad = \quad w\,d^+ \; + \; w\,d^-$$

Subject to :

$$Ax \; - \; I\,d^+ \; + \; I\,d^- \quad = \quad b$$

$$Bx \quad (\geq, =, \leq)\ h$$

$$x_j,\ d_k^+,\ d_k^- \;\geq\; 0$$

where

$j \quad = \quad 1, \ldots\ldots\ldots\ldots, n.$

$k \quad = \quad 1, \ldots\ldots\ldots\ldots, m.$

$d_k^+ . d_k^- = 0$ for $k = 1, \ldots\ldots\ldots, m.$

w = 1 * m vector of weighted or unweighted priority factors

d^+, d^- = m * 1 vectors representing +ve and -ve deviations

A = m * n matrix - technical relationships between activity variables and goals.

x = n * 1 vector of decision variable

I = m * m identity matrix

b = m *1 vector of desired attainment levels

B = p * n matrix of technical relations between activity variables and specified constraints on subgoals

h = p * 1 vector of constraint level imposed on subgoals

The model optimises by minimising the aggregate sum of individual positive (+ve) and negative (-ve) deviations from specified goals. Goal programming uses deviation variables (+ve and -ve) in place of slack and surplus variables, and incorporates one or more goal requirements into the objective function via these deviation variables, before focusing optimisation procedure on deviations by placing no value on x_j. Depending on the management goal, d_k^+ variables can be excluded to preclude overachievement and d_k^- variables removed to preclude underachievement. This must be accompanied by relaxation of Type I or II inequalities. Other model components include the absolute constraints of subgoals, i.e., h, which must be satisfied before any attempt is made to meet the goals.

Basic Approach - Ranking and Weighting

When all the objectives of a goal programming model are met simultaneously, then the problem has been solved. However, when one or more goals can be attained at the expense of others, assuming the deviations from goals are commensurable and the objectives are equally valued, then a solution may be obtained by assigning identical objective function coefficients to deviation variables. If goals are competitive and the objectives are not equally valued, then some device must be used to express the ordinal ranking of each goal according to levels of priorities. The idea of assigning ordinal priority factors as objective function coefficients means that some goals are more important than others, thus making the priority and weighting factors rather difficult to determine (Field, 1973).

The deviation from different goals may be cardinally weighted and maximised in a manner similar to LP models (Dyer et al., 1979). Field et al (1980) used preemptive priorities and cardinally weighted goals to find the preferred strategy. The outcomes showed the tendency to produce "inferior solutions" with respect to physical constraints (Field et al., 1980; Dykstra, 1984). The preference structure encountered implied that the satisfying level of higher ranked goals became a binding constraint on lower ranked goals, thus preventing associated trade-offs (Schuler et al., 1977). These findings led to the almost exclusive application of cardinally weighted GP without incorporating preemptive priorities, for forest management problems (Field et al., 1980; Dykstra, 1984).

3.3.2. Forestry Applications of Goal Programming

Field (1973) was the first to apply the GP technique to a forestry problem. His example involved a small woodland property with a twofold objective of providing recreational values and a supplementary source of income, and three sets of constraints on available days, cabin rental rates and part-time harvest crew respectively. The GP problem solution showed the quantitative trade-offs between allowable cut, vacation and income.

GP was used to model the forest management problem by Schuler and others (1977). In their multiple use study (timber, grazing, and game - hunting sports) preemptive priorities and cardinal weights were found adequate. The most apparent difficulties were technically oriented, i.e., the amount of the output that can be anticipated from a given input or the determination of weightings are often not possible.

In general, the application of GP model has been restricted to small problems only, mainly due to computational inefficiencies and information requirements. In forestry applications, Field et al (1979) discovered that minimisation (e.g., cost) elements set up in model formulation would have implementation problems. Dyer and others (1979) recommended that GP is a useful tool for determining a "satisficing" optimum. They showed that application of GP to public resource allocation will not generate Pareto - efficient solutions.

Kao and Brodie (1979) used GP to compromise conflicts among three goals : even - wood flow, regulating stands and maximising PNV from harvests. More effort was required in problem formulation, as these objectives have to be weighted and considered simultaneously. The GP priority - weighted solution was compatible with the comparable single-objective LP solution. However, in general, GP assisted forest managers in meeting their harvest targets as closely as possible.

Goal Programming was developed to address certain weaknesses of conventional LP, and proved to have certain advantages relative to its predecessor. Despite the flexibility and relative simplicity of GP in analysing problems of multiple-objective nature, it is not a mathematical programming technique to be handled casually. It requires a thorough understanding of the decision problem, before GP model can become an effective forest management tool (Dykstra, 1984; Buongiorno and Gilless, 1987).

Chapter 4

4.0. METHODOLOGY OF PROBLEM SCHEDULING WITH THE SCHEDULER SYSTEM

4.1. Introduction

The SCHEDULER System is a microcomputer based Linear Programming model developed by Schurr and Davis (1989), Department of Forestry and Resource Management, University of California, California. The system was developed in recognition of most forest managers' plights over harvest scheduling year after year. The methodology is based on a linear programming model, an analytic tool used in Timber RAM, MUSYC and FORPLAN. However, the system is simplified to a scheduling model designed to cater for the short term harvest scheduling needs of sellers and buyers of forests or a combination of both. The system is characterised by its economic drive to select harvest units under any given set of constraints and assumptions about future markets (Schurr and Davis, 1989).

The system uses commercially available software for IBM personal computers and compatibles. The two primary software packages are:

(1) a spreadsheet program (i.e., LOTUS 123, QUATTRO or EXCEL)

(2) a linear programming package (LINDO)

Any growth and yield simulator can be incorporated into the system depending on the user's need (Schurr and Davis, 1989). The system is designed to assist a timber organisation in three possible ways :

(1) **Seller model :** Timber organisations, companies and forest growers that do not have wood processing facilities, who must sell their timber products to other timber processing companies.

(2) **Buyer model :** Wood processing organisations and companies that own no timber land. It's a situation where the timber company would need to schedule operations on timber land purchased or leased from grower.

(3) **Combination of Seller and Buyer :** Timber companies owning both timber land and processing facilities. The SCHEDULER system provides an efficient decision support system in the scheduling of wood harvesting and wood allocation.

4.2. System Configuration

The SCHEDULER System can run on any standard IBM personal computers (PC) with the following configuration :

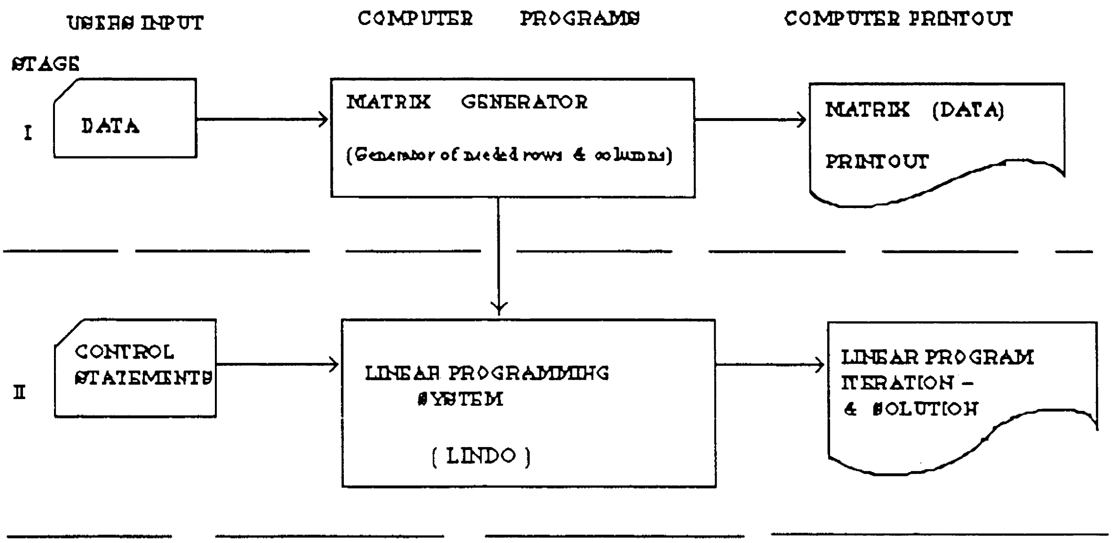
- PC 286 (AT) or 386 with 1 Mbyte RAM
- 40 Mbyte hard disk
- 1.2 Mbyte floppy disk drive (360 Kbyte floppy disk included)
- must have a Math. coprocessor (80*87 chips)
- monochrome or colour monitor
- dot matrix or laser printer

Standard 8086 (PC and XT) machines can be used but have proved very time consuming when running EXCEL and LINDO programs. A lot of storage space is needed and using a 20 Mbyte hard disk drive would require a back-up system every now and then. The hardware system should be equipped with at least a floppy disk drive. A standard 360 Kbyte floppy disk is sufficient. Again, a 1.2 Mbyte 5 1/4 inch and / or 3 1/2 inch drive would greatly increase working speed and information storage. With 640 Kbyte RAM, the SCHEDULER System problem size may be limited. EXCEL or LOTUS 123 spreadsheet requires 640 Kbyte when formulating problems with 150 decision variables. The LINDO executable program occupies 236Kbyte and requires 640 K RAM to run.

The fact is, the larger and faster the computer system the better. This is not always practical and feasible. But, to effectively run the SCHEDULER System and its software package, a microcomputer with not less than an 80286 main processor and an 80287 coprocessor must be available.

The SCHEDULER System contains a system of software packages, all of which are available for use on IBM compatible personal computers. There are two main stages in the process : Matrix Generation and Optimisation of Linear Programming matrix, but it actually takes four steps to get the solution output : spreadsheet , text and equation form, control statements (objective function and constraints), and linear programming package for solution output (Figure 1).

Figure 1 : Linear programming approach in the SCHEDULER System.



The software programs include :

- Spreadsheet programs : LOTUS 123 , QUATTRO or EXCEL :
    - all spreadsheet programs provide an ideal ground for data input with many program commands that make calculation and formulation very easy.

- CONVRT.XLM, an EXCEL macro :
    - to convert LP matrix on EXCEL spreadsheet to TEXT form.

- EQUATION, a PASCAL program for LOTUS 123 or QUATTRO :
    - to convert LOTUS 123 or QUATTRO spreadsheet matrix into conventional equation form compatible with LINDO input information.

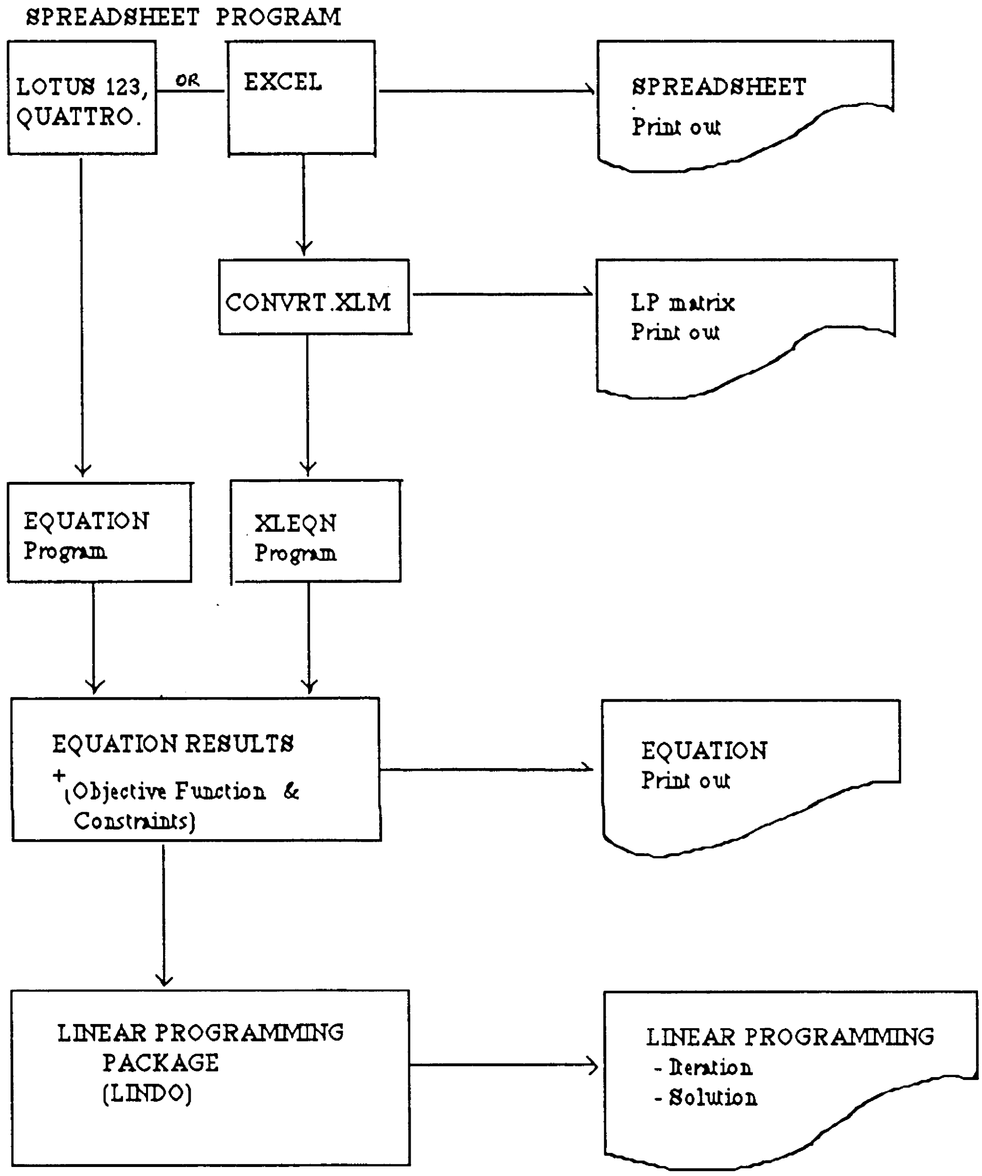
- XLEQN, a PASCAL program for EXCEL :
    - to convert TEXT form information from EXCEL spreadsheet into conventional form for LINDO input information.

- LINDO, a linear programming package.
    - for iteration and solution process.

The SCHEDULER System is similar in many ways to other yield scheduling / optimisation models using LP models (MASH by Weir, 1972; RADHOP for NSW Forest Commission; Timber RAM by Chappelle et al., 1976) but was specifically designed to handle harvest scheduling problems which can be formulated on LOTUS123, QUATTRO and EXCEL spreadsheets (see Figure 2).

The basic ingredients are a series of harvesting units and a list of feasible alternative harvesting strategies. Each harvesting unit is considered homogeneous as harvesting units are representative of age classes. The harvest strategies differ in time and type of treatments. Time of treatment refers to harvesting age of plantation which can be extended to a range of years. Type of treatment refers to the extent of tree removal, which in this situation, is clearfelling. It was apparent that the timing of treatment (rotation age) would have to be determined outside this system.

Figure 2 : Flow Chart of the SCHEDULER System



4.3. The SCHEDULER System Processing Stages

4.3.1. DATA INPUT

The input information defines part of a completely formulated problem whose objective function is to be maximised or minimised under a set of goals and constraints. The goals and constraints that form part of the input information include :

- The number of years in the planning period (Years). This is determined by the extent of timber growth that can be predicted, depending on the reliability of growth and yield model being used.

- The number of sales (Sales) or harvest units and number of prescriptions for each sale (Pr). The prescription includes the sale under any cultural treatment as part of the strategy to be resolved , e.g., clearcutting, thinning or partial harvesting.

  Note : - the software limitations have restricted the number of years, sales and prescriptions to 250 decision variables (Year * Sales * Pr $\leq$ 250).

- Selection of an appropriate discount rate for Present Net Value (PNV) calculation.

- Budget and volume (amount) flow constraints.

- Other relevant economic information as product prices per species, operation costs, etc.

- Other constraints including mill flow, harvest (product) flow, and annual regeneration area goals.

- Other numerical information that will complete the harvesting unit include:
    - size of each harvest unit
    - logging cost
    - defects and damage to product quality and quantity.

It is important to realise that the model output is only as good as the information input. So, the more time spent on effectively collecting information and formulating the problem, the less time spent trying to remedy the problem at the matrix generation stage.

4.3.2. CONTROL STATEMENTS

The control statements which complete the input information into the Linear Programming package include :

- **Objective Function :**

  The attribute to be maximised or minimised. This will be selected as the management objective prior to scheduling or optimisation. Attributes like PNV and Volume are usually maximised while Costs are minimised.

- **Additional Constraints :**

  (1) The product assortments being scheduled. For example, sawlogs and peelerlogs are treated as separate products and the volume production of each is constrained individually as part of total commercial volume. The product differentiation is part of the growth and yield model decided during problem formulation.

(2) Volume to be harvested per harvest area over time. Although it represents the desired wood flow, it can also be constrained by the processing capacity of mills. So, the level of constraints may be subjected to change to satisfy supply and demand aspects to promote a feasible solution.

(3) Other constraints include :

- budget constraints;
- maximum mill volume requirements.
- other economic constraints.

4.3.3. MATRIX GENERATION

The matrix generation stage is characterised by the choice of three types of spreadsheets : LOTUS 123, QUATTRO, or EXCEL to generate input files of selected data for Stage 1. There are two alternatives to present these input data, either to use a Pre-made (pre-format) spreadsheet or to develop one's own spreadsheet format.

1. Pre-made Spreadsheet

The spreadsheet is designed for ease and efficient data entry, formulation and manipulation. However, the size of the pre-made spreadsheet can be limiting, as it can not handle scheduling problems greater than the pre-set size. For example, a spreadsheet divided into a "LP Matrix Section" occupying the upper 46 rows and a "Primary Data Section" in rows 55 - 100, is restricted to that row size, making it difficult to resolve larger scheduling problems (see Figure 3).

2. Creating Own Spreadsheet

This approach allows the creation of a new spreadsheet. The basic layout is in many ways similar to the pre-made spreadsheet in having a "LP Matrix Section" (upper portion) and "Primary Data Section" (lower portion). The flexibility exists to change problem size, as the developer wishes. Firstly, decision variables (columns) and LP equations (rows) must be defined. For example, suppose a harvest scheduling model contains four harvest areas (A,B,C,D), six timber processing centres (S,T,U,V,W,X) and five harvest period (Year 1 - 5). The combination of these factors represent the decision variables. The extent of the decision variables (harvest units * processing centres * harvesting periods) equals 120 decision variables in this example. The top row of columns of LP matrix will have to be entered with the decision variable names, to provide the problem size. Altering columns and rows entries at later stages when processing data can be rather tedious and cumbersome. However, adding extra rows can be done at any time during the problem development. It is only advisable to perfect the outline and define columns and rows before any information is generated.

Figure 3 : **Pre - made Spreadsheet Format**

A B C D .... AK AL AM ....
...

1
2
3 LP MATRIX :
.
. Information for the Planning Problem
.
. (Upper Portion)

46
.
55
.
. PRIMARY DATA
:
.
. Primary information to create LP matrix
.
. * Plantation Data
. * Sale Specific Data
. * Harvest Operation Data
. * Interest / Discounting Rate
.
. (Lower Portion)
100

3. Primary Data Section

This primary information section is designed to hold all relevant data required for the LP matrix generation. Setting up of these data is critical to ensure ease of setting up formulas, block copy, and other useful commands on spreadsheet (see Appendix 1). There is no definite sequence of primary data layout but it can be recorded in the following order :

- **Area data** : The data represent each harvest unit per harvest period. Each data layout can be entered in single row or number of rows for each harvest period.

- **Operation Costs** : Cost details can vary greatly depending on the objective of the problem, e.g., seller, buyer or both. However, the common cost data would include : logging costs, loading costs, hauling costs, administrative costs, etc. The fact that these costs vary with location, distance, volume and time would influence their entry in respective cells.

- **Price data :** Price data would vary with each processing centre due to hauling distance, species, product assortment (sawlogs and peelerlogs), with changes in market prices over time.

- **Interest rate** : An appropriate interest rate for calculating PNV. (4% ; 7%; 10%).

- **Any other information** that will assist the formulation of LP matrix in the upper portion.

The volume data is entered in units of cubic metre per hectare per year (m^3/ha/yr) for year 1 - 5, taking into account the annual increment. Since this information is sale specific, each sale is based on a one hectare (1 ha.) unit area. Financial data including cost of logging ($/m3), administration costs, stumpage rates, haulage costs, mill gate prices per product assortment, interest rates, and other relevant costs and prices need to be clearly stated in each cell. (see Appendix 1).

4. Linear Programming (LP) Matrix Section

The Linear Programming Matrix Section provides information for the planning problem to be solved. Since all rows and columns have already been named at the initial stage, an additional three columns have to be included - VAR, SIGN and RHS. The VAR column will contain names of accounting variables used in each accounting equation row. These are used for intermediate calculations such as costs and returns. A normal constraint row (non-accounting row) will not require an accounting name in the respective cell, e.g., area constraint. The SIGN column will contain one of the following signs (=; ≤; ≥.) as used in the equation. The RHS column will be entered with 0.00 or 0 for accounting rows and 1.00 or 1 for the area rows.

When the framework of the scheduling problem is completely set up in the spreadsheet environment, entries of actual problem matrix or formulas are quite straight forward. Formulation of the problem matrix will include the following information :

Volume Information :

The volume information provides the primary data for problem matrix development. Its entries in the upper rows are important since they will provide the base data for other sections of the matrix. Input into each cell is a formula detailing information like volume per product assortment per hectare. For example, input information into each cell could be a simple copy of a cell value, a product of multiplication, division, addition, subtraction, and aggregates of functions of cell names and so on. Case 1 can be used to illustrate this information input clearly (see Appendix 1) : Cell B2 represents the value of sawlog mahogany / cu.m. / yr1 (SMH1). The values can be entered directly as 151.80 or by typing the equal (=) sign first and then the cell number where the information is located, e.g., +B71 or simply locate and enter cell B71 with the spreadsheet cursor.

Similar entries are carried out for the accounting rows SMH5 and PMH1 - 5. Entries to cells from year 2 - 4 must make a linear interpolation of the volume from year 1 and 5. Therefore, the formula for this approximation can be illustrated as : =+B72 or +B$72 for cell 3; and =+B81 or +B$81 for cell F11. However, if these linear interpolations are available in the primary data section then direct copy can be made using the spreadsheet program's copy command. Total harvest is simply the sum of product assortment per harvest period.

A similar approach is used repeatedly for entries of SMH1 - 5 and PMH1 - 5 to respective cells of decision variables (columns), and using related values from the Primary Data Section. Volume rows are considered as accounting rows, so on the far right, the VAR column has to be entered with accounting row names, having less than 8 characters long of letters and numbers. RHS will be set to zero (0) because of accounting rows with equal (=) signs under SIGN.

Financial Analysis :

To maximise efficient calculation, it is important that revenue and costs are included on the upper rows before generating Present Net Value (PNV) row.

- **Mill Gate Value (MValue)**

Total revenue or MValue of the two products are recorded in 5 years' intake to the respective mills (S & X in Case 1). The formula entered in each cell represents the sum of products of the product prices and product volumes. For example, cell B17 would require the following formula : = +B2 * $B$85 + B7 * $B$91; and =+F6 * $B$85 + F11 * $B$91 for cell F21. The formulas generated for MValue 1 - 5 can be block copied to generate the next MValue1 - 5 of same product destination, e.g., AS1 - AS5; BS1 - BS5; CS1 - CS5; DS1 - DS5. Sets of formulas generated for MValue 1 - 5 of AX1 - AX5 can only be used for BX1 - BX5; CX1 - CX5; DX1 - DX5.

The use of "$" sign is important in formulating these formulas. LOTUS 123 and EXCEL spreadsheets use the "$" sign to prevent updating of the cell locations following the active cell. One must always enter the equal sign (=) first before entering any formula.

- **Total Costs (TCost)**

Total cost represents the last cost calculation of operation costs or other costs that need to be considered in the problem matrix. Logging cost (LCost) is the logging cost times harvest volume per ha. Hauling cost (HCost) represents the product volume hauled times unit cost per cubic metre. For example, Logging cost cell B22 : (B12 * $B$66); cell F26 : (F16 * $F$66). Hauling cost cell B27 : (B12 * $B$68); cell F31 : (F16 * $F$68). These formulas can also be blocked copied in sets of 5 years as previously done with MValue. However, care must be taken as block copying will depend on the set-up of data in the Primary Data Section.

Improper primary data set-up will give incorrect or zero values in input cells.

- **Present Net Value (PNV)**

Profits generated from calculations are entered in rows 37 - 41. Entries of profit values are straight forward using the mouse or formula function of spreadsheet command.

PNV is defined by the formula :

$$PNV = (Profit) / (1 + Int.\ Rate)^{Yr\ in\ Future}$$

PNV formulation as it begins in cell B41 can be demonstrated as : (= + B37 / (1 + $B$97)^B58). B97 indicates the cell location of interest rate in the data section. The year in future follows the harvest period 1-5 from zero to four.

Again, appropriate accounting variables (VAR) and right hand sides (RHS) should be added to the end of rows of the financial analysis : MValue 1 - 5; LCost1 - 5; HCost1 - 5; Profit1 - 5; PNV.

- **Area Constraints:**

To complete the problem matrix, area constraint rows must be added to indicate the term of the scheduling problem. Since each area is unlikely to have more than one harvest for the planning period then value 1 is entered. These rows indicate that each area is to be harvested no more than once during the scheduling period. The entries only include numbers and require no formula.

Area constraint rows are not considered as accounting rows, so the VAR column is left blank. The SIGN and RHS columns entries are as followings : SIGN (≤ or <) and RHS (1 or 1.00).

In equation form, Area A constraint reads as follows :

Area A:

$AS1+AS2+AS3+AS4+AS5+AX1+AX2+AX3+AX4+AX5 \leq 1.00$

similarly, AreaB = AreaC = AreaD $\leq$ 1.00

These equations ensure that the total area cut in each harvest area (A, B, C, D) does not exceed 100% of their total areas.

4.3.4. Linear Program Optimisation

Linear Program Optimisation is the last stage of the SCHEDULER System. This last stage determines "where and how much of the harvest area to cut", based on information provided by the scheduling problem. Once a LP matrix is completed, it must be converted to a compatible equation form by respective programs :

- a LOTUS 123 or QUATTRO problem matrix is translated by the EQUATION program to a spreadsheet print file (ASCII file), a LINDO compatible equation form.

- On the other hand, an EXCEL problem matrix is restructured by the CONVRT.XLM program. The EXCEL text file is then converted by the XLEQN program into LINDO compatible equation form.

The LINDO compatible equations are combined with the Constraint file (ASCII file) containing the objective function and other constraining equations to complete the LINDO equation input file. The LINDO program is a LP solution package to solve the scheduling problem. Given the complete equation file, the LP package through its iteration process will find a set of feasible solutions. Eventually, the LP package will identify the best of the feasible solutions that optimises (maximises or minimises) the objective function and satisfy the set of constraints.

4.3.5. Linear Program Solution Output :

The solution output of LP Optimisation contains optimal values for every variable used in the scheduling problem (Schurr and Davis, 1989). Schrage (1989) showed that solution output from LINDO program can be subdivided into six sections :

(1) Report on Problem Equation : Reproduction of the problem equation as an input file into LINDO program. This is to enhance rechecking of data.

(2) Optimal Solution : It provides the number of iterations required to find the optimal solution including the statement of Optimal Value. A "No feasible solution" is presented in this section when LINDO is unable to find any solution to the scheduling problem.

(3) Variable values and Reduced costs : The Variable and Value columns provide the "where and how much harvest unit to cut per harvest area per year". A zero value in the Value column means that harvest is either not required or delayed due to boundaries of the objective function and constraining factors. A positive Reduced Cost value means that the value of the objective function would decrease by the amount if one unit of the variable were forced into solution. In other words, Reduced cost provides information on opportunity cost of the scheduling problem.

(4) Slack (Surplus) and Dual (Shadow) Prices : A slack (surplus) value is the amount of constraint value that does not contribute to the optimal solution. A zero slack value means that the constraint (RHS value) is limiting or binding. Shadow prices are used in mathematical programming analysis to diagnose which constraints are limiting or binding (Davis and Johnson, 1987).

Therefore, a non-zero shadow price means that it's a value foregone in the objective function to achieve the last unit of constrained output.

(5 & 6) Ranges : Ranges information shows the sensitivity of the solution to changes in objective function coefficients or constraint level. Values in the RHS Ranges are important in checking the stability of the solution.

Chapter 5.

5. The Study Area - The Fiji Forestry Sector

5.1. Background Information

5.1.1. Location and Geographical Features.

The Fiji Islands group is located at approximately *lat.* 15 - 22° S and *long.* 174 - 178° E. It comprises two main islands, Viti Levu has 10,429 sq. km., or 57% of total land area, Vanua Levu - 5,556 sq. km., or 30% of total land area, whilst, the remaining 13% is represented by over 300 islands and islets, making a total land area of 18,282 sq. km. Most larger islands are of volcanic origin with smaller islands mainly of limestone or atoll.

Topographically, the interior of these main islands are very rugged, consisting of mountain ranges and ridges reaching altitudes of 1,324 metres (m) (Mt. Victoria) in Viti Levu, and over 1,000 m in Vanua Levu. The coastal lowland plains including river valleys (< 300 m altitude) provide excellent settlement and agricultural areas. It is estimated that 30% of total land area falls under flat, undulating and rolling hills (2° - 18° slope), as arable areas, while the remainder comprises steep to very steep (> 18°) land.

5.1.2. Climate

Fiji experiences a tropical oceanic climate. Temperature is high throughout the year, ranging from 20.5°C in July to 31.5°C in January, with little difference between day and night, especially along coastal lowlands. The main islands are distinctly divided into two zones (wet and dry) by mountain ranges stretching along the middle of both islands from a north-east to south-west direction. With its South-East Trade wind prevailing all through the year, the south east region (wet zone) receives a greater share of rain than the western region (dry zone).

Fiji's climate is characterised by a wet season (November - April) and a dry season (May - October). Between 1942 and 1986, the seasonal average rainfall was : 450 mm in the dry zone and 1200 mm in the wet zone during the Dry season ; and 1500 mm in the dry zone to 2000 mm in the wet zone during the Wet season. However, rainfall can be quite variable. For example, the short term annual rainfall in the wet zone is generally high, more than 2500 m and averaging between 3000 - 3600 mm, with occasional heavy rainfall even in dry season. The leeward region (dry zone) annual rainfall seldom exceeds 2500 mm, with averages ranging between 1600 and 1700 mm per year. Fiji is located on the tropical cyclone pathway which generally taunt the country once or twice annually. These cyclones have devastating effects on forestry as a major land use.

5.1.3. Geology, Soil and Topography

Fiji's main islands are of volcanic origin, while smaller outlying islands are predominantly limestone. The volcanic nature is characterised by igneous rocks, such as granite, porphyrite, andesite and agglomerate, overlay by Tertiary Miocene, Pliocene and the upper layer Pleistocene sedimentary rocks (tuff, siltstone, conglomerates, mudstones, etc.). These sedimentary rocks can change from neutral to basic with transition from Pliocene to Pleistocene. In the wet zone, sedimentary rocks of basic material are predominant and evenly distributed throughout the interior of the main islands (JICA, 1982).

Topographical conditions and soil characteristics discussed in this report are on the basis of forest management implications rather than other uses. Mixed-hardwood plantation areas, though noncontiguous, ranges from the island's coastal flatland in harvest area A to the north-to-south mountain ranges reaching up to 600m in the interior (harvest area E). A classification of slope distribution in plantation areas can be described as follows :

Slope class	%
< 10%	24.0
10 - 30%	60.0
30 - 45%	16.0
> 45%	0.0

The proportion of convex and concave slopes as related to landform is continually changing with frequent occurrence of landslips on steep gullies, enhancing formation of concave slopes which in general make logging and planting more undesirable. Slope lengths also form constraints on the extent of most forest operations and may be expressed as :

Length of slope > 30%	%
50 - 100 m	55.0
100 - 200 m	35.0
200 - 500 m	12.5
> 500 m	2.5

Generally, soils in most mixed-hardwood areas are humic latosols having deep soils forming reddish clay from basic tuff.

5.1.4. Natural Vegetation

Fiji's natural vegetation cover is typically tropical rainforests in the wet zone with the distinctive feature of grasslands in the dry zone. The vast grasslands in the dry zone are the direct results of humans' abusive use of fire.

The dry zone grasslands consist of mainly : mission grass (*Pennisetum polystachyon*), native fern - qatoqato (*Pteridium esculentum*), reed (*micanthus floridulus*); shrubs and woodland trees : nokonoko (*Casuarina equisetifolia*), vaivai (*Acacia richii*), etc. The general physical characteristics (soil, vegetation, slopes, and climate) of the dry zone provide suitable areas for pine (*Pinus caribaea* var *hondurensis*) plantations.

The composition of the native forests of the wet zones is mainly tropical hardwoods including a few fast growing softwoods and medium hardwoods. These rainforest covers may be divided into four broad categories relating to their location, site condition, species components and climatic conditions : (1) Coastal vegetation, (2) Dry zone vegetation, (3) Intermediate zone vegetation, and (4) Wet zone vegetation. Wet zone vegetation is further subdivided into two category, relating to slope conditions and species composition to delineate "protection forest" from "production forest". Fiji's forest is estimated to cover less than 50% of the total land area (Table 1).

Table 1 : **Natural forest land area**

Forest type	Area (000 ha)	%
1. Production Forests	314.8	36
2. Non - commercial Forests	298.5	34
3. Conservation Forests	250.7	28
4. Mangroves	18.4	2
Total	882.4	100

Source : FFD, 1983 : - Joint Australian / Fiji Review Team - 1986.

In generally, production forests consist mostly of commercially valuable species : Dakua makadre (*Agathis vitiensis*), Kauvula (*Endospermum macrophyllum*), Dakua salusalu (*Decussocarpus vitiensis*), Damanu (*Calophyllum vitiensis*), Kaudamu (*Myristica* spp), Kuasi (*Podocarpus neriifolius*), Mavota (*Gonystylus punctatus*), Rosarosa (*Heritiera ornithocephala*), Rosawa (*Gmelina vitiensis*), Sacau (*Palaquium hornei)*, Yaka (*Dacrydium nidulum*), Yasiyasi (*Syzygium* spp.), etc., and yield at least 30 cubic metre per hectare (m^3 / ha) of commercial volume timber.

Most of the shorelines are covered with mangrove communities : Dogo (*Bruguiera gymnorrhiza*), Tiri wai (*Rhizophora samoensis*), Tiri tabua (*R. stylosa)*, etc.. These covers approximately 18,400 ha. of coastlines. Non-commercial forests are exploitable but yield less than 30 m^3 / ha of merchantable timber. They are characterised by woodlands with partial canopy closure or less complex mixed forest species of intermediate zones and coastal forests. Conservation forest ranges from woodlands and forests of low to moderately stocked forests that cover very steep and rugged slopes. Essentially, these are classified as "protected forests" which also include mangrove areas. These rainforests have an estimated 12.4 million cu.m. of commercial timber, with Viti Levu - 56% and Vanua Levu - 44% (Twyford and Wright, 1965).

5.1.5. Forest Plantations

The forest plantations of the country are divided into two major groups : softwood of mainly *Pinus caribaea* planted on grasslands of the main islands and degraded lands of smaller islands ; and mixed - hardwood plantations established on selectively logged over rainforests of the wet zone (Table 2 (a)).

Table 2 : **Forest Plantation Estates**

Location	Planted area (ha)	Gross area (ha)
(a) Mixed Hardwood Plantations		
1. Southern Division		
- Nuk	7690	7690
- Galoa	6000	6025
- N'tini	3190	6425
- CIS	655	655
- S'kasa	1066	2530
	18601	23760
2. Western Division		
- N'Highland	1300	3290
- N'vatu	3300	6325
	4600	9615

3. Northern division		
- K'tari	1906	2640
- Dreketi	3060	3160
- Wainunu	2422	2475
- Navonu	2765	3450
	10153	11725
Total	33354	45100

Source : FFD Annual Report - 1988

The species selected for planting in mixed-hardwood plantation are chosen after successfully going through a series of trials, which test their capability for the site. However, foreseeing the commercial viability of mahogany, the FFD responded by establishing mahogany on a large scale while having little understanding of proper forest management. Mahogany became a major species of concern to management, and now represent 80 to 90 percent of total area planted. As the FFD moved to diversify its plantations, other timber species were introduced.

The regeneration program on logged over rainforest involves line planting : line weeding (1 metre wide) ; poisoning of non-commercial trees one metre on either side of line weeding ; manual planting at 9m * 4m or 9m * 3m spacing ; spot to line weeding, e.g., up to three times in year 1, up to twice in year 2, and so on. Slow growing species would require many weedings before growing out of competitive weed heights. Justification for thinning mahogany stands was a major concern. There were indications that small scale thinnings have induced the incidence of Ambrosia beetle (*Platypus gerstaegeri*) attack, causing pin holes through the bark and sapwood of growing mahogany trees. Although, it produces no significant physical damage, the resultant small pin holes could influence the timber's marketability purely on appearance. As a result no work plan or management plan was prepared for management of these species, making planting and weeding the only routine annual activities. Obviously, forest management planning was given low priority due to lack of management research and lack of expertise in the field of scientific management planning. Other mixed-hardwood species beside mahogany have been affected by the decision.

A brief summary of the species grown in mixed - hardwood plantations follows :

(1) **Mahogany** (*Swietenia macrophylla* KING).

(Meliaceae)

Mahogany is a tropical American species with its habitat range extending from Mexico to Columbia. Its growth performance has been quite successful, showing minimal growth variation with varying soil types, topography and slopes. Mahogany is a reputable high quality timber species with similar status to teak (*Tectona grandis*), rosewood (*Dyoxylum fraseranum*), Queensland maple (*Flindersia brayleyana*). Mahogany is ideal for wood panelling and general joinery work, boat planking and decking, etc.(Alston, 1982). Its beautiful appearance, stability of size and ease of processing has made mahogany a high class material. The fact that longer rotation promotes higher quality, especially colouration and appearance, is not a factor considered here. The original expected rotation length of 45 years has been reduced to 35 years for economic reasons.

(2) **Cadamba** (*Anthocephalus chinensis* (LAMK.) RICH)

Cadamba's natural region ranges from South East Asia to New Guinea. A fast growing species with very low density timber grown for pulping, interior finishing, moulding, lining, plywood and boxing material (Alston, 1982). It is highly susceptible to cyclone and is site selective.

(3) **Cordia** (*Cordia alliodora* CHAM.)

(Boraginaceae)

Originally from West Indies but has a growth range extending from Mexico to South America. It grows well on moderate to fertile soils on middle slopes but declines in growth as it progresses to lower wet valleys. Cordia is a highly decorative light hardwood, commonly used for wood carving, especially the corestock which has a dark gold colour with dark greenish appearance, similar to Japanese Chishanoki (JICA., 1981). Other uses include light construction, furniture, cabinet making, turnery plywood and interior decoration (Alston, 1982).

(4) **Maesopsis** (*Maesopsis eminii* ENGL.)

(Rhamnaceae)

Maesopsis is a general purpose light hardwood from central Africa. It grows fairly well on all sites but prefers well drained slopes and tolerate lower site quality than other species. It has a tendency to split after cutting and its future use in construction, furniture and cabinet making would be limited to low and medium quality finish (Alston, 1982).

(5) **Kauvula - Fijian basswood** (*Endospermum macrophyllum* (MUELL. ARG.) PAX and K.HOFFM.)

(Euphorbiaceae)

Kauvula is a pioneer species that often appears after forest clearance. Because of this characteristic, kauvula has been included in the group of mixed-hardwood species. It is an excellent timber for general purpose use ranging from fine mouldings, interior finishing, cabinet and furniture, joinery and flooring, plywood, etc. (Alston, 1982). Kauvula is a possible substitute for Malaysian ramin (*Gonystylus spp.*) and a few others, but this would be dependent on management regimes adopted. Estimated rotation is at least 50 years.

(6) **Dakua makadre - Fiji Kauri** (*Agathis vitiensis* (SEEM.) BENTH. and HOOK. f. ex DRAKE)

(Araucariaceae)

Dakua comprises the highest proportion of sawntimber and veneer exports from Fiji's native rainforests and is commercially equivalent to Australian and New Zealand kauri. A highly decorative timber with excellent woodworking properties, Dakua has a wide range of uses from plywood, moulding, interior decoration, furniture, etc.

The Dakua regeneration program is challenged by insufficient research information on site species selection and other management problems relating to mass production for large scale planting. Estimated rotation is at least 100 years.

5.1.6. Land Tenure

Fiji has some 83% (15,255 sq. km.) of its land communally owned by over 6,000 Fijian landowning units. Other land ownership includes private freehold land (10%) and State land (7%). Any alienation (sales) of Fijian native land has been banned by law since the beginning of the century. Therefore, any land development, land use and economic activity on native customary land will require the consents of Fijian landowners and the custodial approval of the Native Land Trust Board (NLTB). The NLTB's mandate ensures that Fijian ownership of land is protected and unused "native land" can be leased out on terms that benefit landowners. In contrast "native reserve" is protected by law from being alienated or leased but can be used solely by villagers for subsistence and communal farming (see Table 3).

Table 3 : **Land ownership by forest type and area (ha)**

Forest Type	Freehold	State	Forest Res.	Leased	Communal	Total
Unexploited production forests [2/]	16,024	6,107	987	3,803	226,312	253,233
Exploited production forests	4,224	1,273	2,271	171	38,775	46,714
Conservation forests	10,941	18,088	13,581	71	208,021	250,701
Non-commercial forest[3/]	13,619	16,776	719	958	219,757	251,829
Mangrove forest		18,400				
Totals	44,808	60,644	17,557	5,003	692,865	820,877

Source : FFD in : Joint Australian / Fiji Review Team - 1986.

From these data, it is apparent that 88% of production forests, 83% conservation forest, and 87% of non-commercial forest are on communally owned land controlled by native customary systems. This makes land acquisition a fundamental issue in any land development program, a factor that can no longer be taken lightly.

5.1.7. Land Capabilities and Land Use Pattern

Land capabilities, land form and climatic features are common factors determining the general pattern of vegetation cover and extent of land use (de Haen, 1988 ; von Maydell, 1987). The dry zone grasslands and degraded lands are direct results of too frequent uncontrolled burning and intensive shifting cultivations (Twyford and Wright,

[2/] Excluding forest plantations
[3/] Excluding exploited production forest

1965). The resulting conditions are incapable of recovery to their original states. These areas suffer from low land capability and are only suitable for low level grazing and reforestation programs. In the wet zone, production and protection forests, including plantations are the major land uses. However, intensive cultivation for commercial farming is predominant on the coastal and alluvial lowlands of both dry and wet zones.

Fiji has abundant land for forestry production but is short of land suitable for agricultural production. Twyford and Wright (1965) and Ministry of Primary Industry (MPI) Land -Use section have attempted to define land capability, based on soil types and slopes for agriculture and forestry as the major land uses (see Table 4).

Table 4 : **Land Capability for Agriculture and Plantation Forestry and Forestry Reserves in Fiji**

	Land Class	Area (sq.km)	% of Total
	Estimates based on MPI (Land Use Section)		
I	Suitable for arable agriculture	2,934	16.0
II	Unsuitable for farming, suitable for tree crops and grazing	7,865	42.8
III	Marginal grazing or forestry	6,523	35.4
IV	Unsuitable (only for forest reserves)	1,057	5.8
	Total	18,379	100.0

The estimates identify 16 - 20% (2,940 - 3,675 sq. km.) of the total area to be suitable for permanent agricultural land without any improvement, a further 10 - 42% (1,838 - 7,719 sq.km.) for agricultural use with minor to major land improvement, while 32 - 35% (5,881 - 6,432 sq.km) is suitable for forestry with the remainder to be retained under forests or other reserves.

The Fiji Employment and Development Mission (FEDM) (1984) compared the land. use survey over two decades (1958 - 78) and highlighted that the area of "land use" has doubled, especially with sugar cane expansion into marginal areas, while subsistence and shifting and cultivation are not recorded (see Table 5).

Table 5 : **Proportion of Land in Use (1958 - 1978)**

Percent of total land area of islands

Island	in use in 1958 (1)	in use 1958 -1978 (2)	in use in 1978 (1) + (2)	% increase of area in use
Viti Levu	10.4	24.3	34.7	233
Vanua Levu	7.2	18.3	25.5	254

Source : Fiji Employment and Development Mission (FEDM), Work and Income for the people of Fiji - "A strategy for more than just survival", Parliamentary Paper No. 66. (1984).

Agricultural development into marginal and forest land can be distinguished in two phases: (1) horizontal growth phase ; and (2) vertical growth phase. Agricultural land use expansion has been focussed solely on phase 1 - the horizontal growth phase, merely converting non-agricultural land viz. marginal agricultural land, woodland and forests, "without" major changes in technology and level of external inputs (de Haen, 1988). Phase 2 - the vertical growth phase, should come into effect when Phase 1 reaches the following limits :

- fallow periods become too short to allow a complete recovery of soil productivity for the next period of cultivation ;
- remaining forest or bush land has reached a minimum, determined by the desired productive or ecological function of trees or forests ;
- new land is physically not available or of such low quality that its productive use would not be profitable ; and
- further farming on remaining unused land would cause unacceptable erosion and nutrient run-off .

The vertical growth phase will depend on changes in technology and investment in land improvements and conservation, but requires intensification of production on a given land base. Fiji agricultural farming has reached, and in many cases exceeded the horizontal growth phase "without" deliberately entering the vertical growth phase (de Haen, 1988). The expansion of agriculture, in particular the sugar cane areas, have exceeded the 20% maximum level of best agricultural land (Class A), now using marginal agricultural land (Class B), and potential forest land (Class C). Comparison of shares of land in use (Table 5) and steep slopes (Table 6), showed a significant proportion of Class B and C land areas are being put under agriculture.

Table 6 : **Proportion of Land with slopes > 18^{o}**

Island	% of Total Area
Viti Levu	67
Vanua Levu	72

Source : Land Use Section - MPI and Twyford & Wright (1965).

Fiji has reached a point in agricultural development, where the limitation of land necessitates a fundamental change towards new forms of more intensive and sustainable land use based on a thorough assessment of the state of land resource and its wise distribution to other major forms of land users (de Haen,1988).

5.1.8. Population and Employment

Fiji's population size reached 715,000 around mid-1986 (Bureau of Statistics, 1988). Fiji may be classified as of low population density with its current 38 persons per sq. km., and average growth rate of 2%. Since 1910, after 75 years, the population has increased tenfold, thereby putting additional pressure on its limited land resource.

Change in population size and structure is a major determinant of the future evolution of Fiji's labour force. A substantial reduction in fertility rates combined with an increase in level of emigration of skilled labour force was evident in 1960 - 1975. This trend was reversed after 1976, when an increased birth rate coincided with stabilisation of levels of emigration. Fertility rates are influenced by socio-economic changes and socio-cultural conditions, which highlighted tensions between ethnic groups in Fiji, in particular, when ethnic Indian population outnumbered the indigenous Fijian population. In late 1980's, levels of emigration increased quite considerably, affecting the rate of population growth. The loss of skilled workers through emigration has been too high and costly to the country. In other words, professional and skilled training have been directed to the wrong people at the wrong time for the wrong reasons.

Fiji is experiencing increasing unemployment (Table 7). This has been accentuated by sharp increases in wages and salaries, especially in the public sector, and with little growth in productivity. In the private sector, similar problems exist but with a difference. The private sector advocates four quick solutions that will have certain "adverse effects" : (1) getting the public sector out of the economy ; (2) capital intensive development of agriculture ; (3) cheap labour manufactured exports ; and (4) cutting of Government spending.

Table 7 : **Population and Employment**

	1976	1982	1985	1987
Population (000)	588	658	699	715
Population (<15 years as %)	41.1	36.8	40.1	42.5
Labour force (000)	175.8	220.4	240.6	247.2
Employment (000)	164.0	202.8	216.1	222.0
Unemployment (000)	11.8	17.6	24.5	25.2
Unemployment (%)	6.7	8.0	10.2	10.2

Source : Bureau of Statistics - 1988

5.2. Fiji Forestry Sector

5.2.1. Forestry Department

The Fiji Forestry Department (FFD) was built on a foundation that took advantage of a favourable position both internally, regionally and at international levels. While the FFD recognised its future would be threatened : by population growth ; by increasing level of protection and sluggish productivity growth ; by growing land constraints ; by undesirable changes in land use pattern ; technical changes and labour costs ; and by infinite conflicting demands on forest resources, it took constructive development measures to complement other forms of development by implementing its National Forest Policy (NFP) within a challenging period of less than four decades.

The NFP was designed to mutually benefit the social, environmental and economic factors of development with particular emphasis on rural areas. One should note that forestry plantations have not gone through a full first rotation cycle. While Fiji's forestry development is still in its juvenile stage and is considered a growth sector, it's yet to experience forestry related problems similar to those in developed and developing countries.

Fiji Forestry development is basically guided by a number of related policies as stated in the NFP viz. :

- Indigenous Forest Policy
- Mixed-hardwood Plantation Policy
- Exotic Softwood Plantation Policy
- Community Forestry Policy
- Environmental - Conservation Policy

Certainly, there are significant overlaps among these policies which make planning process rather difficult, not only at national and divisional levels but mainly at the implementation or operational level.

Indigenous Forest Policy

Indigenous (native) forest management is highly timber production oriented. The upward trend in log production will continue well into the year 2000, until production from plantation is able to sustain wood supply. For example, for the period 1980 - 1985, the maximum allowable annual production was 180,000 m^3, and for the period 1986 - 1990, was increased to 240,000 m^3 per year which was hardly been achieved. The minimum level of log production set in the agreements was considered unimportant.

The FFD plays no direct role in the management of native forests but provides necessary technical advice/information prior to and in control of logging operations and marketing phases. This simply means that landowners have absolute rights and access to the utilisation of their land and forests for "communal use" only. However, exploitation of production native forests for commercial reasons requires certain formalities where the NLTB's approval (under the technical advise of FFD) and consents of landowners are required. Logging licences/agreements are then issued on short (less than 12 months), medium (3 - 5 years), and long terms (10 - 30 years), depending on the extent of the forest resource and the applicant's performance record.

Therefore, the role of the FFD is to technically recommend approval and disapproval of forest exploitations : to sustain native forest supply, long term social and economic benefits to landowners and society, and environmental values of unique forests. In addition, the FFD plays a direct role in :

(1) Logging operation :

- measurement of logs before leaving the forests.
- policing harvesting with respect to logging agreements, e.g., maximising utilisation of commercial timbers and environmental considerations.
- collection of stumpage royalties and fees from log sales
- evaluation of logging operation
- provide training in logging, e.g., National Code of Logging Practice

(2) Timber Processing

- approval of sawmill processing standards (including closing of inefficient mills and new establishments)
- providing training in sawmilling requirements :
    - log grading / specifications / safety
    - timber preservation / seasoning etc.
    - saw doctoring and other maintenance.

(3) Marketing

- quality control for domestic and export markets
- administering import / export regulation of forest products
- advice on timber utilisation to public
- advice on marketing - domestic and international.

Mixed-hardwood Plantations

The indigenous forest program is not totally isolated from other programs. The mixed-hardwood program generally continues the next phase of sustaining wood supply by a regeneration program. The single objective (timber oriented) program is the alternative that translates the legislative requirements and objectives of the Forest Policy into management activities to three divisions with 12 investment centres (Table 2). The objective to transform 100,000 hectares of selectively logged over rainforests into mixed-hardwood plantations by the year 2000, is rather ambitious, especially with inadequate collective planning on the part of the Forestry Department. However, increasing areas are being pursued through investment centres established throughout the wet zones of two main islands, where, in most locations, land becomes available after extensive logging and elaborate land acquisition.

Land Constraints

Some 80% of the total land area is classified as unsuitable for agriculture unless intensified agricultural system is used (Twyford and Wright, 1965 Much of these lands is communally owned and yet, most Fijian landowners have neither capital nor technical know how for their land development. Therefore, the land resource is available for forestry development either as logged over rainforest or to be logged forest. Besides, not all the land resource is suitable for plantation development, and targeted areas are not always readily available except through extensive land acquisitions. As a result these noncontiguous plantation centres are scattered throughout the country, posing an immediate challenge to planners.

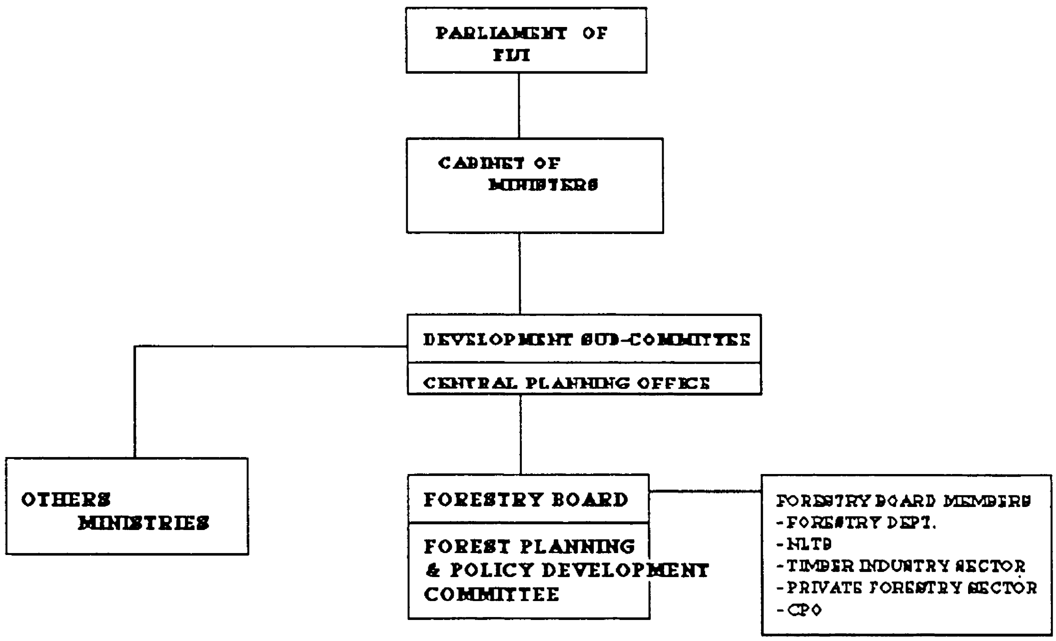
The fluctuating trend of land availability for forestry development will continue well into the year 2000, but is expected to worsen as other forms of land use especially short term - high income earning projects are adopted. The controlling factors that need to be realised is that landowners' consents are essential before any form of land development can be applied.

5.2.3. Fiji Forestry Planning Process

The Fiji forestry sector has for the last four decades anticipated adopting a rational approach to forest planning, but finds itself handicapped by lack of specialists knowledgeable of the socio-economic, biophysical factors, and of forestry development and forestry based planning. Interaction between various disciplines and interest groups is often constrained by differences of priorities, poor communications between and within public and private sectors, and lack of commitment. Restrained by these factors, the forestry planning process becomes too highly centralised for modern forestry planning and decision makings (Figure 4).

The mandate of the Forestry Board is to devise and advise on forestry policies. There are three main policy areas : Forestry Policy ; Timber Industry Policy ; and the Marketing Policy. The Forestry Policy includes the indigenous and plantation forests, and the environmental and conservation policy. The Forest Planning and Policy Development Committee is to devise strategies and develop plans for the National Forestry Sector. In other words, that is the end of the forestry planning process. Division or station level planning remains an ad hoc and informal process, if the planning process exists.

Figure 4 : **Fiji Forestry Policy Development and Planning Process**



Source : FFD - Australian/Fiji Review Team. 1986

The Forestry Headquarters is characterised by a concentration of responsibilities on a few administrators. Their emphasis on strategic or national level planning fails to effectively incorporate the tactical (Divisional) and operational (Station) planning levels. The immediate outcome is that divisional and station levels are dependent on Forestry Headquarters for instructions and directives before management activities are implemented. It is very much a "top-to-bottom" way of communication rather than the preferred two way approach to include the "bottom-to-top" approach.

Computers in Forest Planning.

Microcomputers have become progressively more powerful and inexpensive, paving the way for their use in most aspects of forest planning in many developing countries. In other words, they are becoming very popular, and yet their acceptance by management personnel especially at top management level has been slow in coming.

Many top management staff (who are in command situations) have been suffering from fear of looking stupid when confronted with electronic computers. Microcomputer use has been limited to accounting. Its application to actual forest management planning is yet to be developed. Once developed, it will improve the management's ability to plan and control forest management activities, especially scheduling of "logging operation".

Though not fully realised now, there is a need to accumulate quantitative and qualitative scientific information (forest inventory, environmental, and socio-economic information) necessary to set, for example, management objectives and strategies. A role which modern computers can comfortably accommodate.

5.3. Fiji Timber Industries

5.3.1. Wood Processing Sector

Indigenous Sawmilling

Although the imposition of an import ban (1974) on timber products was to protect local timber industry, it gradually over time forced opportunist sawmills out of production. The anticipated amalgamation of certain sawmills was not apparent except by changing of ownership, and streamlining of timber flow. Since 1986, 53 sawmills have been processing indigenous timber as compared to over 130 in the early 1980s (Alston, 1988). In 1988, a 41% drop in operating sawmills was observed (32 mills), but there was an increase in log intake from 183,508 m^3 in 1986 to 209,712 m^3 in 1988 (Table 8).

Table 8 : **Types of Processing Plants and Production**

Year	Processing mill	No.	Log intake (m^3)
Indigenous Timber Processing			
1986	Sawmill	52	127,537
"	Veneer/plywood	1	55971
1988	Sawmill	32	163,197
"	Veneer/plywood	1	46,515

These data can only indicate :

- increasing log intake for mills with logging concessions
- increasing operating time for family owned sawmills
- more native land being released for logging with reforestation to follow
- consequences of log export (1987 - 1988)

On the other hand, an increase in log intake in no way means that sawmills are becoming efficient. Very little improvement / upgrading of sawmills has taken place since their establishment. The upgrading policy of mills has been pursued quite consistently by the FFD. Studies by Haspey (1984) showed that not only volume but also revenue earnings (both at domestic and export) can increase substantially by including bandsawing into sawmills. Current recovery of 46.7% with circular saws could be increased by at least 5% - 10% (52 - 57%), depending on the level of bandsaw combinations. Using 1984 timber assortment prices, the additional volume would provide an additional revenue of $0.36 million with 74.1% export and 25.9% local markets.

Most of these mills are family owned and there is no real incentive to improve the mill efficiency for several reasons :

- owners have alternative source of income

- unpredictable local market demand for sawntimber
- discontinuities in log supply
- attainment of logging licences is becoming very competitive without any guarantee of long term supply of logs.

While the urge to improve sawmill efficiency will continue for some time, the establishment of new sawmills has come under intense scrutiny. Firstly, there must be a secure forest resource base to ensure continuity of operation on long term basis. Secondly, mill design must incorporate efficient timber processing facilities including available capital for operation backup ; and lastly, there must be joint partnership or involvement of respective landowners in most facets of management activities including share holdings.

There are two transnational owned mills dominating indigenous timber processing including veneer and plywood production. Together with 4 medium size sawmills, their log intake was approximately 56% of total log production in 1988, and continues to increase. The flexibility of medium size sawmills to adapt to the changing technology will be a contributing factor to increasing productivity and quality control in the near future.

Survival of Timber Processing Mills

Survival of these mills is threatened not by their inability to compete in domestic or export markets but whether their forest supplies will last into the next decade. In particular, long term logging concessions for two transnational and medium size mills will expire by 1992 - 1994. Failure to renew logging concession agreements has been largely due to the false promises of the concessionaires and the incompatible expectations of landowners. Although logging agreements are technically sound by ensuring physical environment considerations, social and other biophysical factors have been largely overlooked or ignored.

Presumably, this flaw is common in most previous logging agreements for indigenous forests. Logging agreements are drawn up between the NLTB and the Forestry Department, both of whom underestimate the complex forest ecosystem together with the dynamic landowning communities. Landowners' participation has not been included in the agreement design, because for whatever reasons, they may prejudice the agreement. However, continuing conflicts and protests by landowning communities are indicators of the strained relationships, thus highlighting their role in all aspects of land development and planning including logging agreements.

5.3.2. Logging Sector

Logging in Fiji's context involves optimisation not so much by means of mechanisation but by optimising work organisation from the point of view of productivity, time, and costs. Optimisation based solely on mechanisation (though quite efficient), contradicts the national policy, being socially undesirable because the employment/income distribution in the rural areas is made worse off and it tends to favour multinational agencies. Importantly, the country's intention is to achieve a balance by utilising its increasing labour pool, lower wage rates and employment on semi-skilled and temporary work. The logging sector provides a means of employment for small, independent operators who are not "unionised", in particular the contract logging.

Objectives of Logging.

Logging of native forests has been subjected to great scrutiny and debates over the last decades. So far the objective of logging is to "maximise production at least possible costs", usually resulting in poor logging practices. Hopefully, the implementation of the "National Code of Logging Practices" will promote environmental consciousness, not only among forest operators but throughout the whole forest sector (FFD, 1988).

Mahogany Logging Operation

Mahogany harvesting is in its initial stage. Harvesting data is restricted to clearfelling operation of less than 100 hectares carried out in last three years. An average 7 men team that's equipped with chainsaws, a rubber tyre skidder (Cat 518), and a rubber tyre grapple loader (cat 916) is capable of producing 50 - 60 m^3 per day (FFD, 1988).

Chapter 6

6. Case Study :
Mixed - Hardwood Plantations of the Fiji Forestry Department

6.1. Introduction

The aim of the case study was to investigate the policies of the reforestation program in logged rainforests of the Fiji Islands. To quantify some of these policies such as sustaining wood supply, promoting employment opportunities and regulating income in economically depressed areas and maintaining a sound physical environment requires the application of an array of analytic methods. The case study will attempt to quantify some of the objectives of forest management and tests some alternatives of the plantation and processing sectors. The industrial reforestation program that includes the mixed-hardwood plantation is managed towards achieving two management objectives :

(1) to maximise the forest resource present net value (PNV).

(2) to maximise timber utilisation to the best advantage of the community.

The forest management strategy follows a single objective approach that optimises (maximises) PNV, while promoting employment and income distribution in rural areas. To quantify these objectives, a mixed-hardwood model was used based on the available forestry inventory data and financial information. The problem formulations were resolved by the SCHEDULER System.

The study considers the economic management of forest plantations and silvicultural practices that are consistent with safeguarding the social and physical environment. It is intended to promote the development of management plans at Divisional and Station levels that aim at decentralising certain decision makings. Most importantly, the preparation and coordinated implementation of operation and divisional plans should be based on localised information system.

In the case study, the use of a practical, inexpensive and already developed methodology is tested to assist the forest management decisions on "when, where, and how much" to harvest from each harvest area and the answering of "what if" questions. The adopted method should also be user friendly, giving access to all planners.

6.2. Forest Resource :

The case study areas (A, B, C, D, and E) are part of the industrial mixed-hardwood plantations of the Fiji Forestry Department (Figure 6). It includes 5 of the 12 reforestation centres established on Viti Levu and Vanua Levu islands. These centres represent the older stands of mahogany (90 - 95%) that will be harvested for peeler and sawlogs in the next 2 to 3 decades.

The age-class distribution of the area is irregular due to difficulties in the initial land acquisition (Table 9). Land acquisition is a serious problem that has plagued the program in the past and present, and will continue to do so in the future. However, the major problem now facing forest management planning is the lack of accurate information on the forest resource. The notion of establishing and maintaining forests as cheaply as possible has impaired both plantation protection from disease, fire and wind damage and silvicultural practices standards. It also overlooked the establishment of a sound information base, e.g., plantation maps, species distribution and forest inventory.

Figure 5 : **Distribution of Case Study Harvest Area**

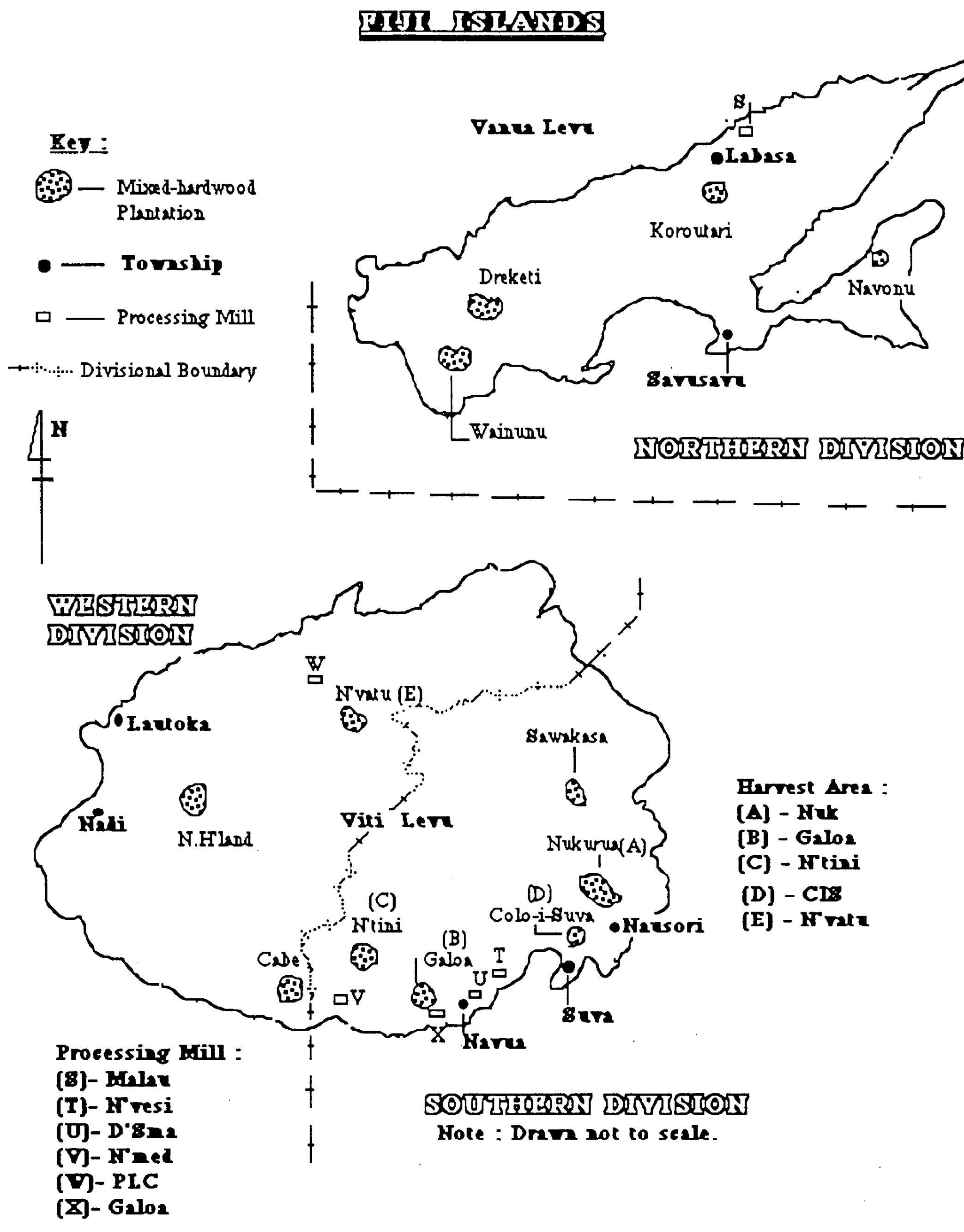


Table 9 : **Area / Age - Class Distribution of the Case Study Area**

Harvest Area (ha)

Age Class (yrs)	A	B	C	D
26 - 30	1100	460	395	250
21 - 25	2400	980	640	210
16 - 20	850	376	327	140
11 - 15	360	356	326	-
6 - 10	730	360	1027	-
1 - 5	250	3466	875	-

Source : Fiji Forestry Dept. Annual Report (1988).

The study area represents 57% (15,878 ha) of the total Forestry Department's mixed-hardwood plantations. An estimated 52% (8,202 ha) of the planted stand is older than 15 years and 42% older than 21 years. The lowest level of planting was in 1975 - 1979 (11 - 15 years), partially due to the ambrosia beetle infection of 1970. The post - 1980 planting has been boosted by a nationwide annual planting program of 5000 hectares , in order to achieve the targeted 100,000 ha by the end of the century.

6.3. Resource Growth and Yield Model

Forest growth and yield modeling can be expressed as mathematical equations or systems of interrelated equations for volume and basal area estimates by computers. These estimates have assisted management decisions on rotations, stand density and the timing of management activities (Clutter et al., 1983). A number of growth and yield equations have been transformed and used in the case study. These equations have expressed the growth and yield per unit area as a function of age, site, and stand density with varying level of complexity and forest species.

One prediction equation was successfully used with the available forest inventory data. The basic Schumacher (1939) yield model estimates the volume as a function of age, site index and some measure of stand density. Equation 1 consistently provided the best estimates of the standing volume throughout the harvest area (A, B, C, D). The equation used the crop mean height (CMH) instead of site index and stand basal area as the parameter for stand density.

$$\ln(\mathrm{Vol}) = \beta_0 + \beta_1 A^{-1} + \beta_2(H) + \beta_3 \ln(B) \qquad (1)$$

where

Vol	=	volume yield per unit area (m^3)
A	=	stand age (yr)
H	=	crop mean height (m)
B	=	basal area

Yield equations per harvest area :

$$\ln(\mathrm{Vol})_A = 1.756 - 0.285\, A^{-1} + 0.102(H) + 0.47 \ln(B)$$

$$\ln(\mathrm{Vol})_B = 3.67 - 14.19\, A^{-1} - 0.045(H) + 0.91 \ln(B)$$

$$\ln(\mathrm{Vol})_C = 2.64 - 5.3\, A^{-1} - 0.01(H) + 0.86 \ln(B)$$

$$\ln(\mathrm{Vol})_D = 1.79 + 1.81\, A^{-1} + 0.004(H) + 0.95 \ln(B)$$

Coefficient of Determination (R^2) $\geq$ 0.97 on all harvest areas.

Equation 1 represents a nonlinear equation which has been linearised. The Student's t-test was used to evaluate the significance of the coefficients of height, age and basal area for each harvest area. The low standard error of estimates and high t-values from the evaluation showed that the coefficients were significant at 5% level. For example, the coefficients of heights and basal areas were significant in the yield estimate. The coefficients of the transformed age were found nonsignificant (at the 5% level) but this variable was retained for consistency with the Schumacher model. Furthermore the test for serial correlation or autocorrelation was found by the Durbin-Watson test to be significant which means that the Student's t-test and F-test would not provide reliable test for significance of these coefficients. However, with the presence of autocorrelation, volume estimates with the linearised Equation 1 would be unbiased and consistent but not as efficient.

6.4. Problem and Problem Formulation

The major problem is that there is no short and long term management plan for the 33,354 hectares (1988) of mixed-hardwood species plantations. The reforestation program activity was biased toward the regeneration areas harvested over the past 2 to 3 decades. Now the need for forest management planning is being realised, in particular for harvesting operations and the regeneration of an even aged plantation program.

A model was prepared using the SCHEDULER System for harvest scheduling of mainly mixed-hardwood plantations. The preparation of any harvest schedule should be the "heart" of any timber management operation. It is primarily through the temporal and spatial scheduling of harvest operations that foresters control the growing stock volume, growth rates, cash flow, present worth, and return on investment (Ware and Clutter, 1971). However, the harvest schedule is of little value if activities such as regeneration, silvicultural practices, protection, harvesting , and marketing are poorly handled. The importance of harvest scheduling is now being recognised and constantly studied to avoid the flaws of past forestry practices.

Since the objectives of the case study was to design harvest schedules that maximise wood value (PNV), the problem formulation was based on the following approaches :

(a) The goal of the reforestation program is the maximisation of utility to the Forestry Department (FD). Assuming the FD is profit oriented, this utility may be measured in terms of quantities such as :

- present net worth, or
- return on investment.

It is assumed that the maximisation of utility is equivalent to the maximisation of the net present worth. This assumption is a considerable abstraction from reality. However, in both intuitive and mathematical decision making, this difficulty is usually circumvented by specifying accepted values for all but one of the objectives and using these values as constraints while optimising the objective (Ware and Clutter, 1971). These objectives which deal with easily conceptualised physical relationships are turned into constraints, leaving only the least clearly defined to optimise as objective, e.g., present net value (PNV).

(b) Factors that influence the maximisation of PNV, e.g., annual harvest unit per class, maximum wood output per age class, and annual wood requirement per mill should be considered in the management alternatives.

(c) Management decisions should remain flexible and sensitive to changes in market conditions, technology, costs and prices. The decision making process should not be strictly confined to long term forest structure objectives.

These conditions suggest that the problem falls into the class of problems soluble by using mathematical (linear - goal) programming techniques. The objective of PNV maximisation is then subject to constraints relating to :

a. harvest areas and productivity (area and yields) based on the prediction of equation 1 (Table 10).

Table 10 : **Yield (m^3/ha) per Harvest area for the 5 and 25 years Cutting Period.**

		Harvest Area			
Cutting Period (Year)		A	B	C	D
1	1990	230	217	205	240
2	1995	240	238	220	270
3	2000	275	263	248	315
4	2005	300	288	279	360
5	2010	338	325	305	380

b. area / age-class distribution of mahogany (Table 9)

c. distribution and capability of timber processing centres (Fig. 6)

Capability of processing centres (m^3/yr)

Periods	S	T	U	V	W	X
1 - 5	75000	50000	25000	25000	50000	100000

Source : Forestry Department Annual Report - 1988.

d. managerial requirements :

1. annual timber supply of $\geq$ 80,000 m^3 and $\leq$ 100,000 m^3.
2. clearfelling will be followed by regeneration.
3. harvesting operations are contract based with the current logging systems and methods based on contract logging.
4. labour availability (skilled and unskilled) in rural areas.

The following technical and economic considerations have been adopted to place the problem formulation within the linear programming framework :

- thinning was not considered in any prescription.
- clearfelling was the only prescription considered.

- analysis period is run in 5 and 25 years.

- three discount rates (4, 7, 10%) have been used for determining PNV.

- current and future mill gate prices based on the current trend (Table 11).

- operational cost includes logging costs per harvest area over time and haulage costs that vary with distance to mill and road conditions.

- other costs, including road construction and maintenance and so on are not considered in the study.

Table 11 : **Processing Centre gate prices of Peeler and Sawlogs ($\$/m^3$)**

		Processing Centres					
Cutting Period		S	T	U	V	W	X
	1	69.0	70.0	69.0	70.0	72.0	70.0
	2	71.0	71.0	70.0	72.0	74.0	74.0
	3	74.0	72.0	71.0	74.0	76.0	78.0
	4	78.0	73.0	72.0	76.0	78.0	82.0
	5	84.0	74.0	75.0	78.0	80.0	86.0
		S		X			
Peeler	1	84.0		90.0			
($\$/m^3$)	2	86.0		95.0			
	3	89.0		100.0			
	4	92.0		105.0			
	5	94.0		110.0			

NB: Processing centres : (a) Integrated mills (S & X)
(b) Sawmills (T, U, V & W)

Source : Personal estimates from FFD Annual Report - 1988.

6.4.1. Problem Formulation

The scheduling problem uses linear programming techniques to determine the harvest pattern by harvesting units that maximise PNV while simultaneously satisfying certain specified restrictions. Harvesting may not necessarily occur in each year of the harvesting period. The planning period (25 years) is divided into "n" (5) harvesting periods of "j" (5) years each and it is assumed that harvesting may occur immediately following the mid-point of each period. It is assumed that after each harvest, replanting follows with the same species and a stock density that would maximise economic yield at the next harvest schedule.

Harvest Areas

There were four harvest areas selected for the case study. These plantations were grouped into areas of similar attributes , in particular, harvest areas of equal age-class distribution of homogeneous stands. The attributes of species and age - class were the only reliable means of delineating these areas for harvesting.

An area control was used, selecting equal areas for the short and medium term cutting periods. In other words, an equal area was set to be harvested per year or period.

Table 12 : Area Control for harvesting per Cutting Period

	Harvest area					
Cutting Period	A	B	C	D	E	Total
3 years	600	270	215	150	60	1295
5 years	1000	450	375	250	-	2075
25 years	5000	2250	1875	1250	-	10375

Source : FFD Annual Report - 1988.

Decision Variables

A harvest scheduling problem which defines "when, where, and how much" timber to cut should have a measure of the area cut as the decision variable or variables controlled by the decision maker. The decision variables represent the various options of managing the harvest areas and the distribution of forest products. The SCHEDULER System then optimises how much of each harvest area to manage under each option. The decision variable represents the number of hectares of each harvest area managed under each option and the distribution of forest products per period.

In the study, the number of decision variables varied with different strategies. For example, Case (1) has four harvest areas, two forest products, two processing centres and five cutting periods, giving a total of 80 decision variables.

Constraints

The scheduling problem had three sets of constraints, i.e., area, volume and processing centres. Within the constraints the plantation must be harvested once during the planning period. The wood flow (volume) is constrained by the processing centres that can process peeler logs, sawlogs or both. The volume constraint is marked by specifying the maximum yield per period and the minimum yield for all harvest periods. For example, a volume control constraint can be represented by the notation :

$$\sum_{i=1}^{s} v_{ij} X_{ij} \leq V_j$$

where

s	=	harvest area
		i (i = 1,....s)
j	=	harvest year
X_{ij}	=	amount of harvest area "i" cut in j^{th} year
V_j	=	volume output in j^{th} year
v_{ij}	=	volume output of area "i" in j^{th} year

The constraint represents the volume output produced in year "j" by harvest area "i". The scheduling problem has no budget constraint. Other forest products including short lengths and fuelwood are not considered in the problem. Three types of constraints can be used in linear programming, i.e., equalities (=), greater than or equal to (≥), and less than or equal to (≤). The constraints are distinguished from the objective function by the presence of equalities and inequalities at the right hand sides of the equations.

Objective Function

The management objective is to optimise (maximise) the timber values or PNV (5 or 25 years) on investment in mixed-hardwood plantations. Therefore, because it is an economic objective, it only make sense to measure the objective in amount of dollars. The objective function can also be defined to optimise (maximise) the physical output of the harvest area or quantity (volume, m^3) of timber. The mixed-hardwood model which uses linear programming only optimises one objective for a given model run.

The optimal value for the economic objective function represents the set of numerical values for the decision variables, i.e., the number of hectares harvested from each area and each period. From this the quantity of forest product can be derived as input into the processing centre.

In mathematical notation, the objective function for the scheduling problem may be expressed as :

$$Z = C_1X_1 + C_2X_2 + \ldots\ldots\ldots\ldots + C_nX_n$$

or

$$\text{Max } Z = \sum_{i=1}^{n} C_i X_i$$

where

Z = a symbolic value of the objective - PNV.

C_i = dollar value contribution per hectare of harvest area.
[the coefficient ($ / m^3 / mill)]

X_i = number of hectares for each decision variable.

6.4.2. Mathematical Statement of the Mixed-hardwood Model

The linear programming model used in the scheduling problem represents a class of forest planning model belonging to the "Model 1" group of Johnson and Scheurman (1977). In the study, each harvest area with each age-class at the beginning of the planning period was identified and preserved through the planning horizon. The age-class was taken as a reasonable approach for modeling the mixed-hardwood because it can later be subdivided into subcompartments when the information of the appropriate analysis area becomes available.

The mixed-hardwood model was developed to investigate some relationships in the harvesting and wood allocation between some old plantations and processing centres. Other models could also be formulated to resolve similar problems.

The set of decision variables already expressed can be used to formulate a mathematical model as :

Objective function :

$$\text{Max PNV} = \sum_{i=1}^{s} \sum_{k=1}^{m} \sum_{j=1}^{n} C_{ijk} \quad X_{ijk}$$

Subject to

(a) Area Control

$$\sum_{k=1}^{m} X_{ijk} \leq Y_i \quad \text{(for all values of i and j)}$$

(b) Volume Control per Period

$$\sum_{i=1}^{s} \sum_{j=1}^{m} v_{ijk} X_{ijk} \leq V_j \quad \text{(for all values of j)}$$

(c) Total volume (maximum)

$$\sum_{i=1}^{s} \sum_{j=1}^{n} \sum_{k=1}^{m} v_{ijk} X_{ijk} \leq W$$

(d) Processing centre intake

$$\sum_{i=1}^{s} v_{ijk} X_{ijk} \leq M_{jk} \quad \text{(for all values of j \& k)}$$

and

$$X_{ijk} \geq 0$$

where

X_{ijk} = amount of area "i" harvested in year "j" destined to mill "k".

C_{ijk} = contribution (pnv) to objective function from harvest area "i" in jth year for mill "k".

Y_i = area (ha) of harvest area "i".

V_j = volume output per harvest area in year "j".

M_{jk} = volume intake per processing centre "k" in year "j".

W = total volume needed to be produced over the planning period.

for

i = 1, 2 ....s
j = 1, 2 ...n
k = 1, 2 ...m

where

s = 4
n = 3 , 5 , or 25
m = 2 or 6

6.5. Management Alternatives

The management strategies of the case study considered the various management options that affect the value of harvested mahogany , the utilisation of mahogany and rural participation in the wood industry by the yield control and timing of the harvest. The harvest strategies at different levels of harvest were constrained by area or volume control and the capacity of wood processing centres. The area control was based on the writer's local experience of the unsurveyed plantations to avoid any overcutting. It was also intended for an even-aged regeneration strategy. Land, labour and budget were not considered as constraints in the case study.

The yield control maintains a non-declining flow of wood over time. The total volume harvested in any period is constrained by the potential yield of the harvest area, downstream processing, and marketing prospects. For example, a management strategy may be restrained by restricted wood flow to maximise the value of mahogany timber on targeted markets. The same mixed-hardwood model was used in every problem formulation (Case 1 - 4). However, constraints were varied to provide information for each management option.

These case studies were selected to investigate the area and volume control of four harvest areas and the wood allocation to six processing centres. Wood allocation to each processing centre was controlled to investigate any relationship between the resource, haulage distance, price and the capability of processing centres. Two planning periods were used in the case study. The 3 - 5 year planning period represents the Operational level (Divisional and Station) (Case 1 - 3) and the 25 years planning period the Divisional and National level (Case 4).

6.5.1. Case 1 : Non - declining flow to integrated mills

A non - declining wood flow over a 5 year cutting period was used. Besides the required scheduling information, Case 1 was to provide additional information on the supply of mahogany logs to mills that promotes processing into value added products.

6.5.2. Case 2 : Non - declining flow to integrated and sawmills

Unlike Case 1, Case 2 scheduled the harvest volume to 6 mills, i.e., two integrated mills and four medium size sawmills scattered in the proximity of the mixed-hardwood plantations. Although Case 2 attempted to maximise the timber value, it was equally concerned with the future of existing indigenous timber sawmills, now facing an uncertain future wood supply.

6.5.3. Case 3 : Wood flow with increasing harvest areas

Case 3 represents the expansion of the harvest area and the addition of mature plantations into the harvest scheduling problem. Three discounting rates (4, 7, and 10%) were used in the short term harvesting problem.

6.5.4. Case 4 : Sensitivity of PNV to Rotation and Conversion Period

Case 4 represents the three different rotation ages and their impacts on the PNV. Different values of volume intake were used in the processing centre constraints to check the directional change in wood flow and effects on harvest areas.

Chapter 7

7. Results and Discussions

These results are part of the problem solutions produced by the Linear Programming System (LINDO), known as the Linear Programming : iteration and solution (Fig. 2). A sample of the problem solution printout of the SCHEDULER System is given in Appendix 2.

The first part of the LINDO output file shows the number of iterations at which the LP optimum was reached in Appendix 2 and the value of the objective function ($29.0 million). This is followed by three columns namely Variable, Value and Reduced Cost. The Value column contains the optimal values of the decision variables. A zero value in the Reduced Cost column means the Variable is optimised. A non zero value in the Reduced Cost means that the value of the objective function would decrease by the Reduced Cost amount if one unit of the variable were forced into solution.

The second part of the output file shows the Slack or Surplus and the Dual or Shadow Prices. For example, the zero Slack values for Rows (equations) 2 to 26 shows that all the areas and wood volume were harvested, and the right hand side (rhs) values of the constraints were limiting or binding. However, the Slack value of the AX1 (Row 27) equation shows that an additional wood volume of 10,000 m^3 from harvest area A could be harvested and delivered to X in Year 1, and Row 28 indicates an excess of 14,029 m^3 in Year 2. The non zero Shadow Price value means that the area or volume control is limiting. For example, the non zero Shadow Price values (Rows 2 - 21) represent the amount the value of an objective function (PNV coefficient) would change when one or more unit of an area control constraint is increased or reduced.

The Ranges information of the third part of the printout summarises the list of decision variables and slack variables that have non zero values in the optimal solution. Included are the allowable increase and decrease columns that show the minimum and maximum boundaries of changes before the *basis* [4/] could change.

The last part of the sample printout provides the allowable changes in the right hand side values of the equation before any change in the objective function could be detected. For example, the right hand side value of harvest area A (year 1) could be increased to 379.8 hectares or reduced to 187.8 hectares from its current level of 200 hectares before the basis could change.

7.1. Case 1

Case 1 shows a non-declining flow of forest products for sawntimber and veneer production. The wood supply has ensured that a sufficient quantity of assorted forest products is available throughout the planning period. However, the solution often favours the supply of logs to processing centre "X" (74%). Apparently, the volume control constraint placed on "X" has forced the supply of remaining forest products to processing centre "S" (26%) (Table 13 a.). The distribution of areas harvested is shown in Table 13 (b).

Table 13 (a) : Area allocation per harvest area for each processing centre and the 5 year Cutting Period

	Processing Centre with Cutting Period										
H/area	S1	S2	S3	S4	S5	X1	X2	X3	X4	X5	TOTAL
A	110.4	104.9	91.1	-	-	89.6	95.1	108.9	200	200	1000
B	-	-	-	-	-	90	90	90	90	90	450
C	75	75	75	30.6	23.4	-	-	-	44.6	51.6	375
D	-	-	-	-	-	50	50	50	50	50	250
Total	185.4	179.9	166.1	30.6	23.4	229.6	235.1	248.9	384.6	391.6	2075
%	8.9	8.7	8.0	1.5	1.1	11.1	11.3	12.0	18.6	18.9	100.1

[4/] A basis is the list of decision variables that have non zero vale in the optimal solution

Table 13 (b) : Distribution of harvest areas (%) to Processing Centres

	S (%)	X (%)
A	31	69
B	0	100
C	74	26
D	0	100

The non-declining flow of wood supply has reached an acceptable volume in the first five years of harvest with sawlogs averaging 66% and peelerlogs 34%. It is acceptable enough as it approaches the country's average log intake for period 1984 - 1988 (100,000 m^3). The net revenues based on the mill gate values less the logging and hauling costs, were estimated as \$5.89 million in year 1 to \$8.90 million in year 5. The maximum PNV was estimated at \$31.66 million. (Table 14 (b)).

Table 14 (a) : Volume of Product Assortments harvested in the 5 year Cutting Period

	Cutting Period				
	1	2	3	4	5
Sawlog (m^3)	61320	63230	65150	67070	69090
Peelerlog(m^3)	31590	32700	33650	34550	35540
Total (m^3)	92910	95930	98800	101620	104630

Table 14 (b) : Cost and Revenue Estimates for the 5 year Cutting Period

	Cutting Period (to nearest \$1000)				
	1	2	3	4	5
Logging cost	327	368	393	427	395
Hauling cost	721	757	758	431	515
Total cost	1048	1126	1152	859	911
Revenue	6939	7659	8194	9079	9815
Net Revenue	5891	6533	7042	8220	8904
PNV	5891	6106	6157	6709	6797
Total PNV	31660				

Discussion : Case 1.

The LP solution of the SCHEDULER System maximises the PNV at $31.6 million for the 5 year cutting period. This effectively means that a cubic metre of forest product is worth more financially and economically in the next 5 years. This is assuming that the data and information used in the problem formulation remain realistic.

The wood flow and wood utilisation from the harvest areas (A, B, C, D) to the two integrated mills (S and X) were maximised when X received 74 percent of the total wood supply. The average harvest volume of 98,760 m^3 per year will pose no immediate difficulty to the harvesting operation since there is no shortage of workers. Harvesting and its associated activities will create employment in this sector of the operation.

The extent of harvesting will not have any detrimental effects on the environment with the implementation of the Code of Practice (FFD, 1988) that provides standards for the harvesting operations. The alternative has maximised the sawlog consumption but could not meet the minimum peeler log intake. The results have indicated that the alternative is economically feasible. The results also showed that the wood flow to the processing centres can be easily controlled by varying the right hand side values of the volume intake constraints. The approach has practical application in wood allocation to the integrated mills for the process of value added products.

7.2. Case 2.

Case 2 solution represents the distribution of forest products to other sawmills (T, U, V, W) in addition to the integrated mills (S and X). The wood supply to these sawmills is constrained by the fact that they process sawlogs only and by their reduced processing capacity. Wood supply to these sawmills were drawn only from harvest area"A." The solution also means that the integrated mill "S" was receiving the least wood supply with all of harvest areas B, C, D, and about half of A being scheduled for mill "X." (Table 15 (a)).

The harvest areas of Case 2 have not changed from that of Case 1. Therefore, the area harvested per year does not change but the distribution of forest products to processing centres varies quite markedly. These sawmills do not purchase peelerlogs unless peelerlogs are sold at sawlog prices. The solution also showed that the hauling cost has become an important factor in the distribution of forest products.

Table 15 (a) : Area allocation per harvest area to each processing centre

	Harvest Area			
Processing Centre	A	B	C	D
S1	12.4	-	-	-
S2	11.1	-	-	-
S3	13.7	-	-	-
S4	-	-	-	-
S5	-	-	-	-
T1	32.9	-	-	-
T2	32.0	-	-	-
T3	31.2	-	-	-
T4	-	-	-	-
T5	-	-	-	-
U1	32.9	-	-	-
U2	32.0	-	-	-
U3	31.2	-	-	-
U4	-	-	-	-
U5	2.8	-	-	-

V1	32.9	-	-	-
V2	32.0	-	-	-
V3	31.2	-	-	-
V4	27.8	-	-	-
V5	17.6	-	-	-
W1	65.8	-	-	-
W2	64.1	-	-	-
W3	50.0	-	-	-
W4	-	-	-	-
W5	-	-	-	-
X1	23.1	90	75	50
X2	28.6	90	75	50
X3	42.6	90	75	50
X4	172.2	90	75	50
X5	179.6	90	75	50

Table 15 (b) : Volume of Product Assortments harvested in the 5 year Cutting Period

	Cutting Period				
	1	2	3	4	5
Sawlogs (m^3)	61320	63230	65150	67070	69090
Peelerlogs(m^3)	31590	32700	33650	34550	35540
Total (m^3)	92910	95930	98800	101620	104630

Table 15 (c) : Cost and Revenue Estimates for the 5 year Cutting Period.

Cutting Period (to nearest $1000)

Operation	1	2	3	4	5
LC	277	315	330	403	439
HC	276	328	381	566	647
Total	553	643	712	969	1087
Revenue	5824	6357	7006	8828	9624
Net rev.	5271	5714	6294	7859	8537
PNV	5271	5449	5629	6082	6614
Total PNV	29045				

Discussion : Case 2.

An important feature of this alternative was the increase in processing centres to include the sawmills. The maximum PNV was estimated at $29.0 million for the 5 year cutting period. While maintaining the same harvest areas and wood volume as in Case 1, the only obvious change was the shift in the distribution of the forest products. With 73 percent of the total harvest area (2075 hectares) being scheduled for clearcutting and delivery to mill "X," the future of the remaining 5 mills is rather doubtful.

The increasing hauling cost has influenced the direction of wood flow, especially to processing centres in the proximity of the harvest areas. For example, the favourable location of the mill "X" has contributed greatly to the acquisition of the greater supply of forest products. The wood allocation in harvest area A did not necessarily maximise the distribution of forest products. Sawlogs and peelerlogs were supplied to each sawmill causing a reduction in the total PNV.

The constraint for each processing centre has enabled the harvesting of all the harvest areas in the five year period. The clearcut areas would be regenerated, allowing the establishment of more even - aged forests. Although the intention was to keep these sawmills operational, the solution has suggested otherwise. Unless these sawmills become competitive economically, they would be overtaken by the redistribution of forest products to the large integrated mills. It is apparent from the solution that medium to large integrated mills in the proximity of the harvest areas provide the best financial return to the grower or seller of forest products.

7.3. Case 3.

Case 3 solution represents how an additional harvest area would influence the outcome of a harvest scheduling problem. Beside the expected increase in wood supply, the distribution to respective mills is controlled by economic factors (Table 16 (b)). The present net values by three discount rates (4, 7, 10%) were estimated at \$18.7, \$17.8 and \$17.3 million respectively. These estimates were based on five harvest areas (A - E), two processing centres (S & X), and a 3 year scheduling period (1 year per period). The problem shows that the harvest area is limiting as all the areas allocated have been scheduled for clearcutting in the planning period. However, harvest area D has 8.8 and 18.1 hectares remaining after the first and third cutting period (see Table 16 (a)).

Table 16 (a) : Area allocation per harvest area to each processing centre

	Processing centre						
Harvest area	S1	S2	S3	X1	X2	X3	TOTAL
A	111.3	107.8	100.9	88.7	92.2	99.1	600
B	-	-	-	90	90	90	270
C	-	-	-	75	75	75	225
D	-	-	-	41.2	50	31.9	123.1
E	20	20	20	-	-	-	60

Table 16 (b) : Volume of product assortments (m^3) harvested per Cutting Period

	Period 1	Period 2	Period 3
Sawlog	62700	65900	64600
Peelerlog	32300	34000	33400
Total	95000	99900	98000

The harvest volume represents 34% peelerlogs and 66% sawlogs.The operation cost, revenue and present net value per period (7%) discount rate can be summarised (Table 16 (c)).

Table 16 (c) : Cost and Revenue Estimates for the 3 years Cutting Period

	Cutting Period	(to nearest $1000)		
Operation	1	2	3	
Logging cost	329	351	351	
Hauling cost	862	897	847	
Admin. cost	26	27	25	
Total	1217	1276	1223	
Revenue	7082	7736	7958	
Net Rev	5865	6460	6735	Total
PNV	5864	6037	5882	17784

Discussion : Case 3.

The effect of an additional harvest area (E) was immediately apparent in the problem solution. The wood flow from the harvest areas A, B, C, and D continues to favour the wood supply to mill "X", with only part of A and all of E to be harvested and delivered to mill "S." The reduced harvesting in area D meant that the wood intake by mill "X" was limiting on the first and third cutting periods. The LP solution shows that it is more economical to reduce the harvest area and therefore volume than to accept the high haulage cost to mill "S." The increase in harvest revenue was nullified by the increased harvesting cost. This means that a small increase in harvest area per cutting period will not contribute positively to revenue and PNV.

Clearly, the increasing high operation cost will continue to influence the future net revenue. For example, the haulage cost is approximately 70 percent of the total operation. An alternative to contain the increasing cost would mean the delineating of harvest areas into zones based on economically feasible haulage distance between the grower and the processor or establishment of processing centres in the proximity of the plantation areas. It is apparent that the plantation operations cannot be looked at in isolation, as the processing sector and market conditions need to be incorporated into the planning.

Results of the three discounting rates for the 3 cutting years have shown that it will have a major impact on the value of these plantations. Although past regeneration and maintenance costs were not available, it was apparent a 10 percent discount rate would require a shorter financial rotation or an early harvest commencement age. On the other hand, a lower discount rate (4 percent) could mean a longer rotation, thus giving greater yield or production of high quality and high valued peeler logs.

7.4. Case 4 : 25 year Cutting Period

Case 4 represents the solution to the medium term (25 years) scheduling problem. The alternative uses the same harvesting areas, financial data and processing centre constraints presented in Case 1. The main feature of Case 4 was the comparison of the three rotation ages (35, 40 and 45 years). A non-declining wood flow was observed among the three rotations. However, there was a marked change in the product assortments (peeler and sawlogs). For example, the longer the rotation the greater the proportional increase in peeler log production , thus generating higher revenue for higher valued products (Table 17 (b)).

The volume control has ensured not only the continuity of wood flow throughout the planning horizon but also guaranteed a viable timber industry. However, the distribution of forest products often favours mill "X." The wood supply to mill "S" in the 35 year rotation represented a mere 16 percent of the 10,375 hectares for the 25 year cutting period. This increased to 36 percent in the 40 and 45 year rotation age cases (Table 17 (a)).

Table 17 (a) : Area allocation (ha) per harvest area to each processing centre for the three rotation ages.

Processing Centre "S"

	35 year Rotation				40 year Rotation				45 year Rotation			
	A	B	C	D	A	B	C	D	A	B	C	D
S1	278.4	-	375.0	-	460.4	-	375.0	-	428.7	-	375.0	-
S2	-	-	375.0	-	471.4	-	375.0	-	291.8	-	375.0	-
S3	-	-	375.0	-	534.7	-	375.0	-	320.6	-	375.0	-
S4	-	-	147.3	-	199.3	-	375.0	-	356.5	-	375.0	-
S5	-	-	152.7	-	146.4	-	375.0	-	383.4	-	375.0	-
%	6	0	76	0	36	0	100	0	36	0	100	0

Processing Centre "X"

	35 year Rotation				40 year Rotation				45 year Rotation			
	A	B	C	D	A	B	C	D	A	B	C	D
X1	721.6	450.0	-	250.0	539.6	450.0	-	250.0	571.3	450.0	-	250.0
X2	1000.0	450.0	-	250.0	528.6	450.0	-	250.0	708.2	450.0	-	250.0
X3	1000.0	450.0	-	250.0	465.3	450.0	-	250.0	679.4	450.0	-	250.0
X4	1000.0	450.0	227.7	250.0	800.7	450.0	-	250.0	643.5	450.0	-	250.0
X5	1000.0	450.0	222.3	250.0	853.6	450.0	-	250.0	616.6	450.0	-	250.0
%	94	100	24	100	64	100	0	100	64	100	0	100

Table 17 (b) : Total Volume of product assortments harvested per Rotation Age (m^3 / Period)

	1	2	3	4	5
Sawlog	329600	337800	346000	354300	362000
Peelerlog	177500	183500	186300	190700	194900
35 yr Rotation	507100	521300	532300	545000	556900

Sawlog	341800	349300	356900	364500	372300
Peelerlog	227800	233800	237900	243000	248200
40 yr "	569600	583100	594800	607500	620500
Sawlog	348300	355200	362200	370500	377500
Peelerlog	284900	291600	296300	303100	308800
45 yr "	633200	646800	658500	673600	686300

The proportion of peeler logs harvested per cutting period increase with rotation age. This was reflected in the revenues as peeler log revenue exceeded that of sawlogs in the longest rotation (45 years). The high timber utilisation was marked by an uniform increase in net revenues (Fig. 6) and PNV per rotation age (Fig.7 & Table 17 (c)).

Figure 6 : Net Revenue - Case 4.

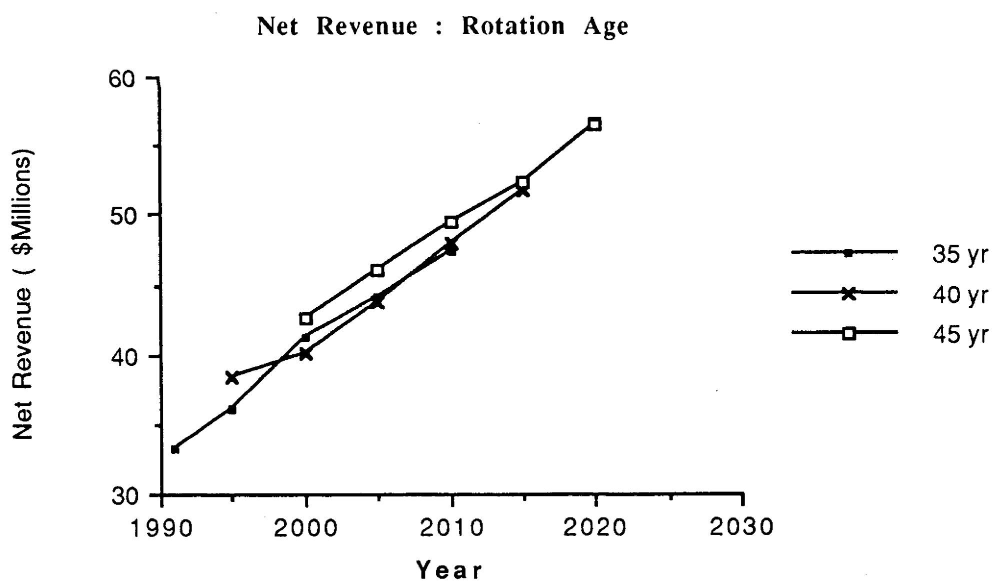


Figure 7 : PNV of the three rotation ages - Case 4.

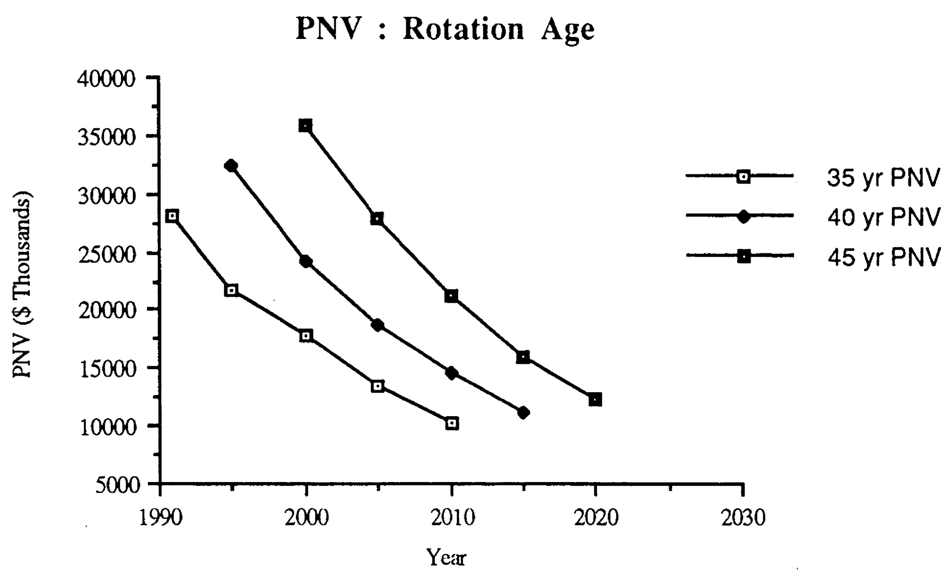


Table 17 (c) : Present Net Value (PNV per Period) of the three rotation ages (to nearest $1000)

	1	2	3	4	5
35 yr Rotation	28000	21700	17600	13500	10300
Total PNV	91300				
40 yr "	32400	24100	18700	14600	11200
Total PNV	101000				
45 yr "	35900	27700	21200	16000	12300
Total PNV	113000				

Discussion : Case 4.

The problem solutions provided by the three rotation ages have portrayed a uniform pattern of wood flow as constrained by the area and volume control. The non-declining wood flow showed that all the harvest areas have been clearcut and distributed to the respective mills. The solution also showed that the values of PNV were sensitive to changes in the processing centre constraints. For example, a 16 percent reduction in the right hand side values of mill "X" constraints have increased the distribution of wood flow to mill "S" by 19 percent for the 40 and 45 years cutting periods. Although the shift in wood supply was to keep "S" operational, this didn't maximise the net revenues and PNV. This alternative means that the 35 year rotation would maximise the net revenue and PNV. The 45 year rotation could provide a better alternative, since it maximises the production of high quality and valued product such as peeler logs. So, to maximise timber values in the longer rotation would mean restraining wood flow to mill "S" and stabilising the wood volume intake to mill "X."

The harvest area of 10,375 hectares represents 32 percent of the total plantation area (1988) or 65 percent of the study area (15,880 hectares) (Table 9). The periodic harvesting area of 2,075 hectares means that the three harvest ages could be adopted depending on the objectives of the forest management. One could only opt for the longer rotation where a premium is payable for the high quality and high valued forest products such as peeler logs.

7.5. Summary of Results and Discussions

In general, the problem solution from the SCHEDULER System is based on a single objective approach and is largely timber oriented. The key feature of the problem is to maximise timber value or PNV. The area and volume control have ensured the maintenance of a viable timber industry both in the short and medium terms. The constraints set by the processing centres have not only enabled the clearcutting of all the harvest areas, but also tested the competitiveness of these processing centres to acquire these forest products. The fact that the data and information input into the scheduling problems were limited to that currently available means that the problem solutions from the SCHEDULER System could be improved once better data and information become available. This could bring a clear understanding of the problem and the solution system. Most importantly, the SCHEDULER System was designed for short term harvest scheduling problems. The system has its limitations when used for longer term scheduling.

The problem solutions are presented at two levels, the 1 year period (5 years planning horizon) and the 5 year period (25 years planning horizon). Both approaches were restricted by the area and volume control throughout the planning horizons. Notably, clearcutting was the only prescription used. It is economically favourable in the sense that it maximises the PNV. It is environmentally desirable because of the minimal disturbance to the harvest areas when applied in noncontiguous small compartments. Plantation regeneration would follow immediately after clearfelling to maintain an even aged plantation. Although thinning was not considered in the management strategy for biological reasons, it could favourably complement the increasing periodic PNV.

The key feature of the problem was the maximisation of the timber value or PNV. This was achieved through the Case 1 alternative in the short term and Case 4 on the medium term. The problem solution of Case 4 (45 years rotation) has shown that the revenues from the peeler logs surpassed that of sawlogs.

The short term problem solutions (Cases 1, 2 & 3) exemplified the effects of the constraints by harvest areas, volume and the processing centres on the objective function (PNV). By comparison, Case 1 has not only maximised the wood flow to the integrated mill, but also generated a high PNV. On the other hand, Case 2 maximises the wood flow to both the integrated mills and the sawmills but could not produce a higher PNV (Table 18) .

Table 18 : **Estimates of PNV by the four case studies**

Cutting Period	Case No.	Interest rate (%)	PNV ($ million)	Rotation length (yrs)
3 years	3	4	18.73	30
3 years	3	7	17.81	30
3 years	3	10	10.31	30
5 years	1	7	31.66	30
5 years	2	7	28.91	30
25 years	4	7	91.38	35
25 years	4	7	101.25	40
25 years	4	7	113.41	45

The periodic PNV of the two alternatives have shown that Case 1 was more economical of the two alternatives (Fig. 8). It was also apparent from the cost estimates that the hauling costs have incurred the highest of operation costs (Fig.9). The high hauling cost of Case 1 was related to the wood flow to mill "S" in the first three years as the constraint on mill "X" was limiting. A comparison of net revenues for Cases 1 and 2 also showed that Case 1 was the better alternative (Fig. 10).

Figure 8 :

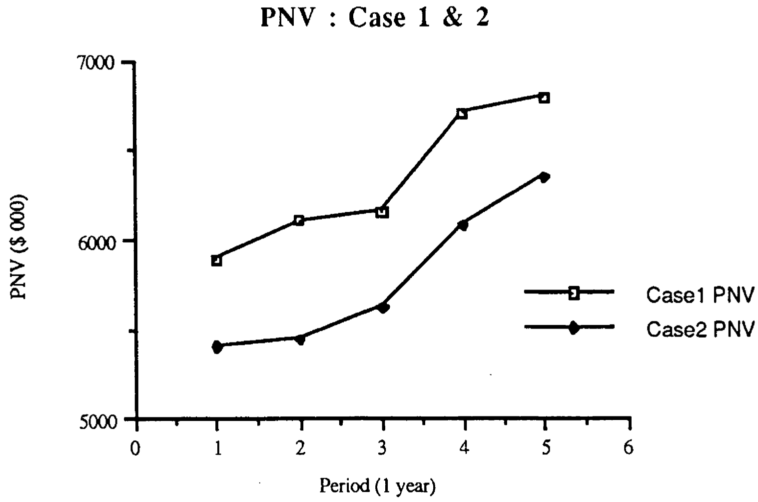


Figure 9 :

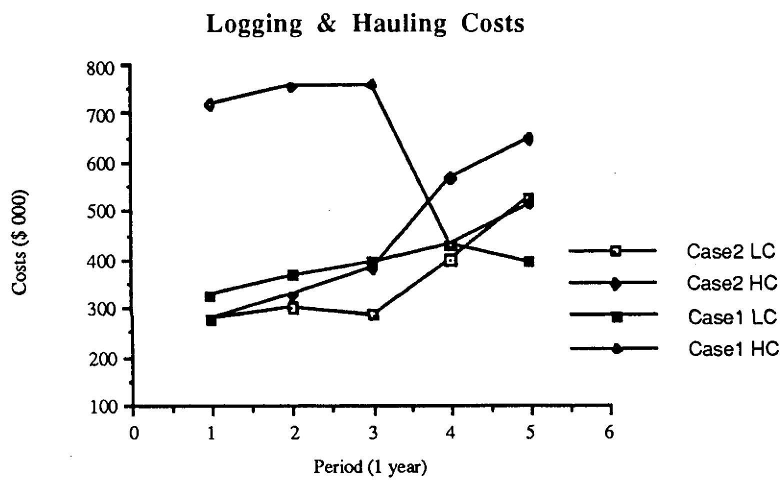
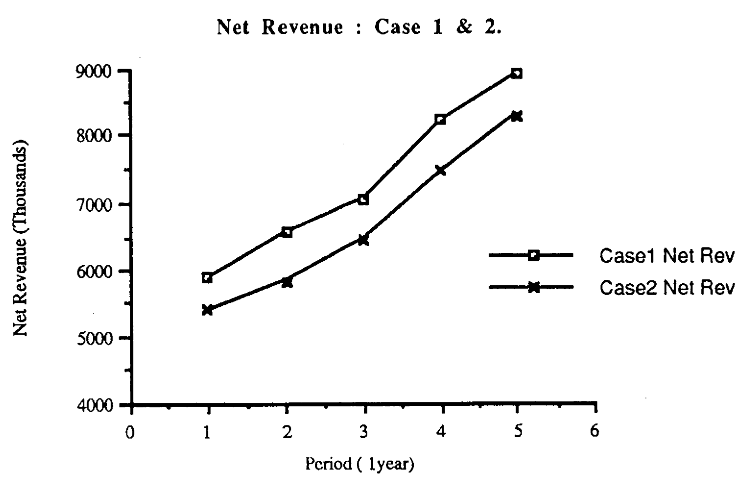


Figure 10 :



Based on these results, the short term wood allocation exemplified in Case 1 provides the best alternative for management planning. The effects of different discounting rates are shown in Case 3 (Table 18).

The 25 year problem solutions have provided a similar pattern of development as shown in the short term scheduling. The non-declining wood flow to the processing centres continued throughout the scheduling period but tends to favour mill "X" for economic reasons. The declining wood flow to mill "S" is related to the high haulage cost rather than its wood volume intake constraint. The alternative has shown that the longer rotation would maximise the timber value, due to the premium payment for high quality and valued forest products.

Given the problem solutions of the case studies, in particular, the effects of the available data and information, the writer can now foresee the feasibility of the SCHEDULER System, not only in the scheduling of harvest operations, but also in assisting the preparation of management plans for the mixed-hardwood plantations of the Fiji Forestry Department. Each case has its practical application depending on the local management objectives. The model has the flexibility to cope with technical, economic, social and political issues and the compromise among these issues.

Chapter 8

Conclusions

The case study findings have demonstrated that the SCHEDULER System, a microcomputer package for short term harvest planning can be adopted as an introduction to advanced forest planning in the Fiji Forestry Sector. It has been shown that the scheduling system can easily provide the outcomes of alternatives taken prior to the formulation of forest harvesting and management plans. The flexibility of the system to model the role of the forest grower (seller), buyer or the combination of both has offered greater insights into the forest management problems currently facing the forestry sector.

The SCHEDULER System is user friendly on microcomputers, at least an IBM or IBM compatible such as an AT286 or 386. Although the scheduling system is quite flexible, it requires a familiarity with the microcomputer system and its application, and a knowledge of the computer programs that run the SCHEDULER System. The construction and running of a scheduling problem can also be greatly enhanced by a better understanding of the problem, a better understanding of the problem model and the methodologies of linear programming, plus the problem data and information for different management alternatives.

The mixed-hardwood plantation model uses the available forest inventory data, representing the plantations as they are now for the problem formulation. The quality and quantity of data may be rather limited for detailed problem formulation ; however, it has provided the initial working information to be improved upon when better information is available.

The objective function in all the scheduling alternatives has been the maximisation of the timber PNV. Other non-financial objectives that could be optimised include the maximising of the harvest volume or the minimising of the harvest costs. Because of the general similarities in the harvest areas, the designed mixed-hardwood model can be applied in all the plantation areas.

The solutions to the short and medium term planning problems involving the integrated mills and sawmills seemed quite acceptable. Improved data quality and information is required for a sound data and information base. Sensitivity analysis needs to be used to investigate variability in the model. The local forest plantation development is subject to many changing influences, including the market conditions and destructive agents such as tropical cyclones and insects attack. Most importantly, the current problem formulation is centred on one of the five timber species in the mixed-hardwood plantations. A shift to a species type basis rather than the age-class distribution would add more flexibility and complexity to the problem formulation. Even though the SCHEDULER System was applied only to the mixed-hardwood plantations, it can also be used for softwood plantations and native forest harvesting given the availability of sound data and information.

As mentioned earlier, the target of the Forestry Reforestation Program is too ambitious and was evidently set without a comprehensive planning analysis or was otherwise based on an optimistic view of a better market for specialised forest products. Perhaps that's exactly what is happening now, only to be assisted with the adoption of the improved planning technology.

Although the intention of the study was to test the feasibility of the SCHEDULER System in assisting the decision making and as an introduction to advanced forest planning, the search for solutions to many of the underlying problems affecting scheduling and planning cannot be resolved entirely by system analysis. The SCHEDULER System is not and should not be used as a substitute for other working models, if any. It can be introduced to complement existing or yet to be introduced models to enhance forest management planning. It could merely be an introduction to a more advanced planning model to be adopted at a later stage. However, for a small and developing country like Fiji, it would be an appropriate starting point for such deliberations.

8.1. Recommendations

This study has shown that forest management planning can be greatly assisted by the application of appropriate mathematical programming techniques, in particular the linear programming models. Based on the information used in the study, it can be recommended that :

(1) Fiji's forest planning process should evolve as its developed neighbouring countries have, in order to handle modern forestry problems, for example, by using computer based mathematical programming techniques to resolve forest management problems and to enhance the decision making process.

(2) Divisional and station level planning should dominate the preparation of harvest and regeneration scheduling including budgetary and manpower planning, in other words, the partial decentralisation of the planning and decision making process.

(3) Longer rotation ages (45 years and over) should be selected to favour the production of high quality and high valued forest products for integrated mills rather than sawmills.

(4) Economic working zones between the integrated mills and the plantation sites should be delineated based on haulage distances, markets and so on, in order to maximise wood value and wood production.

8.2. Further work

To get the maximum benefits from the application of mathematical programming techniques, further studies on the following are recommended :

(1) To improve forest information such as forest inventory and production data, financial and economic data, and social and environmental data.

(2) To develop forest growth and yield models for each timber species and harvest area, both for current and future growth and yield forecast including product assortments.

(3) To develop LP models that optimise (maximise) the timber values and timber production by each mixed-hardwood timber species for longer periods (greater than 50 years).

(4) To broaden the work on decision support systems to include the multiple objectives of forest management.

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Appendix 1 : Case 1 : Sample spreadsheet with formulas

	AS1	AS2	AS3	AS4	AS5	AX1	AX2	AX3	AX4
SMH1	=+B71					=+B$71			
SMH2		=+B$72					=+B$72		
SMH3			=+B$73					=+B$73	
SMH4				=+B$74					=+B$74
SMH5					=+B$75				
PMH1	=+B77					=+B$77			
PMH2		=+B$78					=+B$78		
PMH3			=+B$79					=+B$79	
PMH4				=+B$80					=+B$80
PMH5					=+B$81				
THARV1	=SUM(B2:B11)					=SUM(G2:G11)			
THARV2		=SUM(C2:C11)					=SUM(H2:H11)		
THARV3			=SUM(D2:D11)					=SUM(I2:I11)	
THARV4				=SUM(E2:E11)					=SUM(J2:J11)
THARV5					=SUM(F2:F11)				
MValue1	=+B7*$B$91+B2*$B$85					=+G2*$G$85+G7*$G$91			
MValue2		=+C8*$B$92+C3*$B$86					=+H3*$G$86+H8*$G$92		
MValue3			=+D9*$B$93+D4*$B$87					=+I4*$G$87+I9*$G$93	
MValue4				=+E10*$B$94+E5*$B$88					=+J5*$G$88+J10*$G$94
MValue5					=+F11*$B$95+F6*$B$89				
LogCost1	=+B12*B$66					=+G12*G$66			
LogCost2		=+C13*C$66					=+H13*H$66		
LogCost3			=+D14*D$66					=+I14*I$66	
LogCost4				=+E15*E$66					=+J15*J$66
LogCost5					=+F16*F$66				
HCost1	=+B12*B$68					=+G12*G$68			
HCost2		=+C13*C$68					=+H13*H$68		
HCost3			=+D14*D$68					=+I14*I$68	
HCost4				=+E15*E$68					=+J15*J$68
HCost5					=+F16*F$68				
TCost1	=+B22+B27					=+G22+G27			
TCost2		=+C23+C28					=+H23+H28		
TCost3			=+D24+D29					=+I24+I29	
TCost4				=+E25+E30					=+J25+J30
TCost5					=+F26+F31				
Profit1	=+B17-B32					=+G17-G32			
Profit2		=+C18-C33					=+H18-H33		
Profit3			=+D19-D34					=+I19-I34	
Profit4				=+E20-E35					=+J20-J35
Profit5					=+F21-F36				
PNV	=+B37/(1+$B$97)^0	=+C38/(1+$B$97)^1	=+D39/(1+$B$97)^2	=+E40/(1+$B$97)^3	=+F41/(1+$B$97)^4	=+G37/(1+$B$97)^0	=+H38/(1+$B$97)^1	=+I39/(1+$B$97)^2	=+J40/(1+$B$97)^3
AreaA	1	1	1	1	1	1	1	1	1
AreaB									
AreaC									
AreaD									

DATA LINE		************		*************		**************		************	
TIMBER SALE	UNIT COSTS								
HA	A	B	C	D					
YEAR1	200	90	75	50					
YEAR2	200	90	75	50					
YEAR3	200	90	75	50					
YEAR4	200	90	75	50					
YEAR5	200	90	75	50					
	A1	A2	A3	A4	A5	A1	A2	A3	A4
LC($/m3)	3.38	3.55	3.76	3.91	4.11	3.7	3.89	4.08	4.28
	AS1	AS2	AS3	AS4	AS5	AT1	AT2	AT3	AT4
HC($/m3)	18.72	18.83	18.93	18.94	18.96	2.2	2.9	3.6	4.1
YIELD PER CUTTING PERIOD									
	A	B	C	D					
YEAR1	151.8	143.22	135.3	158.4	sawlog				
YEAR2	156.42	147.84	138.6	165					
YEAR3	161.04	152.46	141.9	171.6					
YEAR4	165.66	157.08	145.2	178.2					
YEAR5	170.78	161.7	148.5	184.8					
YEAR1	78.2	73.78	69.7	81.6	peeler				
YEAR2	80.58	76.16	71.4	85					
YEAR3	82.96	78.54	73.1	88.4					
YEAR4	85.34	80.92	74.8	91.8					
YEAR5	87.72	83.3	76.5	95.2					
MILLGATE PRICES ($/M3)									
	S	T	U	V	W	X			
YEAR1	69	70	69	70	72	70	sawlog		
YEAR2	71	71	70	72	74	74			
YEAR3	74	72	71	74	76	78			
YEAR4	78	73	72	76	78	82			
YEAR5	84	74	75	78	80	86			
YEAR1	84	0	0	0	0	90	peeler		
YEAR2	86	0	0	0	0	95			
YEAR3	88	0	0	0	0	100			

YEARS	94	0	0	0	0	110
	0.07		interest rate			

Appendix 1 : Case 1 Standard Spreadsheet

	AS1	AS2	AS3	AS4	AS5	AX1	AX2	AX3	AX4	AX5	BS1	BS2	BS3	BS4	BS5	BX1	BX2	BX3	BX4	BX5	CS1	CS2	CS3	CS4	CS5	CX1	CX2	CX3	CX4	CX5	DS1	DS2	DS3	DS4	DS5	DX1	DX2	DX3	DX4	DX5	VAR	SIGN	RHS
SMH1	151.80					151.80					143.22					143.22					135.30					135.30					158.40					158.40					SMH1	=	0.00
SMH2		156.42					156.42					147.84					147.84					138.60					138.60					165.00					165.00				SMH2	=	0.00
SMH3			161.04					161.04					152.46					152.46					141.90					141.90					171.60					171.60			SMH3	=	0.00
SMH4				165.66					165.66					157.08					157.08					145.20					145.20					178.20					178.20		SMH4	=	0.00
SMH5					170.78					170.78					161.70					161.70					148.50					148.50					184.80					184.80	SMH5	=	0.00
PMH1	78.20					78.20					73.78					73.78					69.70					69.70					81.60					81.60					PMH1	=	0.00
PMH2		80.58					80.58					76.16					76.16					73.10					71.40					85.00					85.00				PMH2	=	0.00
PMH3			82.96					82.96					78.54					78.54					73.10					73.10					88.40					88.40			PMH3	=	0.00
PMH4				85.34					85.34					80.92					80.92					74.80					74.80					91.80					91.80		PMH4	=	0.00
PMH5					87.72					87.72					83.30					83.30					76.50					76.50					95.20					95.20	PMH5	=	0.00
THARV1	230.00					230.00					217.00					217.00					205.00					205.00					240.00					240.00					TH1	=	0.00
THARV2		237.00					237.00					224.00					224.00					211.70					210.00					250.00					250.00				TH2	=	0.00
THARV3			244.00					244.00					231.00					231.00					215.00					215.00					260.00					260.00			TH3	=	0.00
THARV4				251.00					251.00					238.00					238.00					220.00					220.00					270.00					270.00		TH4	=	0.00
THARV5					258.50					258.50					245.00					245.00					225.00					225.00					280.00					280.00	TH5	=	0.00
MValue1	17043.00					17664.00					16079.70					16665.60					15190.50					15744.00					18239.40					18432.00					MV1	=	0.00
MValue2		18035.70					19230.18					17046.40					18175.36					16127.20					17039.40					19025.00					20285.00				MH2	=	0.00
MValue3			19300.40					20857.12					18272.10					19745.88					17006.50					18378.20					20566.00					22224.80			MV3	=	0.00
MValue4				20772.76					22544.82					19696.88					21377.16					18207.20					19760.40					22345.20					24251.40		MV4	=	0.00
MValue5					22591.20					24336.28					21413.00					23069.20					19665.00					21186.00					25368.00					26364.80	MV5	=	0.00
LogCost1	777.40					851.00					733.46					802.90					692.90					758.50					912.00					816.00					LC1	=	0.00
LogCost2		841.35					921.93					795.20					871.36					751.54					816.90					997.50					1142.50				LC2	=	0.00
LogCost3			917.44					995.52					868.56					942.48					808.40					877.20					1079.00					975.00			LC3	=	0.00
LogCost4				981.41					1074.28					930.58					1018.64					860.20					941.60					1188.00					1063.80		LC4	=	0.00
LogCost5					1062.44					1163.25					957.95					1102.50					924.75					1012.50					1290.80					1156.40	LC5	=	0.00
HCost1	4305.60					506.00					4426.80					288.61					1575.22					410.00					5882.40					1128.00					HC1	=	0.00
HCost2		4462.71					687.30					4793.60					320.32					1732.47					567.00					6352.50					1300.00				HC2	=	0.00
HCost3			4618.92					878.40					5174.40					353.43					1812.88					817.00					6944.60					1482.00			HC3	=	0.00
HCost4				4753.94					1029.10					5593.00					387.94					1929.84					1078.00					7700.40					1674.00		HC4	=	0.00
HCost5					4901.16					1344.20					6002.50					428.75					2226.15					1147.50					8274.00					1932.00	HC5	=	0.00
TCost1	5083.00					1357.00					5160.26					1091.51					2268.12					1168.50					6794.40					1944.00					TC1	=	0.00
TCost2		5304.06					1609.23					5588.80					1191.68					2484.01					1383.90					7350.00					2442.50				TC2	=	0.00
TCost3			5536.36					1873.92					6042.96					1295.91					2621.28					1694.20					8023.60					2457.00			TC3	=	0.00
TCost4				5735.35					2103.38					6523.58					1406.58					2790.04					2019.60					8888.40					2737.80		TC4	=	0.00
TCost5					5963.60					2507.45					6960.45					1531.25					3150.90					2160.00					9564.80					3088.40	TC5	=	0.00
Profit1	11960.00					16307.00					10919.44					15574.09					12922.38					14575.50					11445.00					16488.00					PRO1	=	0.00
Profit2		12731.64					17620.95					11457.60					16983.68					13643.20					15655.50					11675.00					17842.50				PRO2	=	0.00
Profit3			13764.04					18983.20					12229.14					18449.97					14385.22					16684.00					12542.40					19767.80			PRO3	=	0.00
Profit4				15037.41					20441.44					13173.30					19970.58					15417.16					17740.80					13456.80					21513.60		PRO4	=	0.00
Profit5					16627.61					21828.83					14452.55					21537.95					16514.10					19026.00					15803.20					23276.40	PRO5	=	0.00
PNV1	11960.00					16307.00					10919.44					15574.09					12922.38					14575.50					11445.00					16488.00							
PNV2		11898.73					16468.18					10708.04					15872.60					12750.65					14631.31					10911.21					16675.23						
PNV3			12022.05					16580.66					10681.40					16114.92					12564.61					14572.45					10955.02					17265.96					
PNV4				12275.01					16686.30					10753.36					16301.94					12584.99					14481.78					10984.76					17561.51				
PNV5					12685.12					16653.11					11026.45					16431.20					12598.53					14514.84					12056.19					17757.45	PNV	=	0.00
AreaA	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00																																<	1.00
AreaB											1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00																						<	1.00
AreaC																					1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00												<	1.00
AreaD																															1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		<	1.00

DATA LINE ************* ************** ************ ************ *********** *********** *********** *********** *********** *********** ***********

TIMBER SALE UNIT COSTS

HA	A	B	C	D
YEAR1	200.00	90.00	75.00	50.00
YEAR2	200.00	90.00	75.00	50.00
YEAR3	200.00	90.00	75.00	50.00
YEAR4	200.00	90.00	75.00	50.00
YEAR5	200.00	90.00	75.00	50.00

	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B1	B2	B3	B4	B5	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5
LC($/m3)	3.38	3.55	3.76	3.91	4.11	3.70	3.89	4.08	4.28	4.50	3.80	3.99	4.15	4.40	4.61	3.40	4.57	3.75	3.94	4.13	3.38	3.55	3.76	3.91	4.11	3.70	3.89	4.08	4.28	4.50	3.80	3.99	4.15	4.40	4.61	3.40	4.57	3.75	3.94	4.13
	AS1	AS2	AS3	AS4	AS5	AT1	AT2	AT3	AT4	AT5	BS1	BS2	BS3	BS4	BS5	BT1	BT2	BT3	BT4	BT5	CS1	CS2	CS3	CS4	CS5	CT1	CT2	CT3	CT4	CT5	DS1	DS2	DS3	DS4	DS5	DT1	DT2	DT3	DT4	DT5
HC($/m3)	18.72	18.83	18.93	18.94	18.96	2.20	2.90	3.60	4.10	5.20	20.40	21.40	22.40	23.50	24.50	1.33	1.43	1.53	1.63	1.75	22.60	23.70	24.80	25.80	29.10	2.00	2.70	3.80	4.90	5.10	24.51	25.41	26.71	28.52	29.55	4.70	5.20	5.70	6.20	6.90

PER CUTTING PERIOD

	A	B	C	D	
YEAR1	151.80	143.22	135.30	158.40	sawlog
YEAR2	156.42	147.84	138.60	165.00	
YEAR3	161.04	152.46	141.90	171.60	
YEAR4	165.66	157.08	145.20	178.20	
YEAR5	170.78	161.70	148.50	184.80	
YEAR1	78.20	73.78	69.70	81.60	peeler
YEAR2	80.58	76.16	71.40	85.00	
YEAR3	82.96	78.54	73.10	88.40	
YEAR4	85.34	80.92	74.80	91.80	
YEAR5	87.72	83.30	76.50	95.20	

MILLGATE PRICES ($/M3)

	S	T	U	V	W	X	
YEAR1	69.00	70.00	69.00	70.00	72.00	70.00	sawlog
YEAR2	71.00	71.00	70.00	72.00	74.00	74.00	
YEAR3	74.00	72.00	71.00	74.00	76.00	78.00	
YEAR4	78.00	73.00	72.00	76.00	78.00	82.00	
YEAR5	84.00	74.00	75.00	78.00	80.00	86.00	
YEAR1	84.00	0.00	0.00	0.00	0.00	90.00	peeler
YEAR2	86.00	0.00	0.00	0.00	0.00	95.00	
YEAR3	89.00	0.00	0.00	0.00	0.00	100.00	
YEAR4	92.00	0.00	0.00	0.00	0.00	105.00	
YEAR5	94.00	0.00	0.00	0.00	0.00	110.00	

0.07 interest rate

Appendix 2. Sample of the SCHEDULER System Solution Output

LP OPTIMUM FOUND AT STEP 1688

OBJECTIVE FUNCTION VALUE

1) 29046450.0

VARIABLE	VALUE	REDUCED COST
AS1	12.439360	.000000
AS2	11.120710	.000000
AS3	13.688020	.000000
AS4	.000000	4106.000000
AS5	.000000	3812.000000
AT1	32.894740	.000000
AT2	32.051280	.000000
AT3	31.250000	.000000
AT4	.000000	135.000000
AT5	.000000	130.000000
AU1	32.894740	.000000
AU2	32.051280	.000000
AU3	31.250000	.000000
AU4	.000000	338.000000
AU5	2.780957	.000000
AV1	32.894740	.000000
AV2	32.051280	.000000
AV3	31.250000	.000000
AV4	27.809920	.000000
AV5	17.647060	.000000
AW1	65.789470	.000000
AW2	64.102560	.000000
AW3	50.000000	.000000
AW4	.000000	527.000000
AW5	.000000	300.000000
AX1	23.086960	.000000
AX2	28.622880	.000000
AX3	42.561990	.000000
AX4	172.190100	.000000
AX5	179.572000	.000000
BS1	.000000	4258.765000
BS2	.000000	4379.254000
BS3	.000000	4984.166000
BS4	.000000	8244.145000
BS5	.000000	7305.354000
BT1	.000000	1034.384000
BT2	.000000	1227.274000
BT3	.000000	1863.765000
BT4	.000000	1206.145000
BT5	.000000	1575.354000
BU1	.000000	913.462600
BU2	.000000	1144.427000
BU3	.000000	1822.916000
BU4	.000000	1347.145000
BU5	.000000	1501.354000
BV1	.000000	791.824400
BV2	.000000	1158.351000
BV3	.000000	1969.965000
BV4	.000000	1283.145000
BV5	.000000	1822.401000
BW1	.000000	909.929600
BW2	.000000	1202.216000
BW3	.000000	1934.265000
BW4	.000000	1969.145000
BW5	.000000	2000.354000
BX1	90.000000	.000000
BX2	90.000000	.000000
BX3	90.000000	.000000

BX4	90.000000	.000000
BX5	90.000000	.000000
CS1	.000000	1088.278000
CS2	.000000	1387.220000
CS3	.000000	1480.719000
CS4	.000000	5042.637000
CS5	.000000	5177.724000
CT1	.000000	1310.002000
CT2	.000000	1609.259000
CT3	.000000	1552.519000
CT4	.000000	1574.637000
CT5	.000000	1770.724000
CU1	.000000	918.817900
CU2	.000000	1220.566000
CU3	.000000	852.250500
CU4	.000000	667.636700
CU5	.000000	268.723600
CV1	.000000	560.390300
CV2	.000000	942.412500
CV3	.000000	956.869200
CV4	.000000	910.636700
CV5	.000000	1106.853000
CW1	.000000	563.811200
CW2	.000000	982.143400
CW3	.000000	1006.457000
CW4	.000000	1455.637000
CW5	.000000	1571.724000
CX1	75.000000	.000000
CX2	75.000000	.000000
CX3	75.000000	.000000
CX4	75.000000	.000000
CX5	75.000000	.000000
DS1	.000000	1032.365000
DS2	.000000	1171.034000
DS3	.000000	1153.599000
DS4	.000000	5444.190000
DS5	.000000	5377.404000
DT1	.000000	841.286400
DT2	.000000	1077.014000
DT3	.000000	940.399000
DT4	.000000	893.190400
DT5	.000000	1049.404000
DU1	.000000	709.233700
DU2	.000000	967.860700
DU3	.000000	819.817900
DU4	.000000	965.190400
DU5	.000000	823.404300
DV1	.000000	701.325900
DV2	.000000	844.937500
DV3	.000000	641.249100
DV4	.000000	325.190400
DV5	.000000	500.316100
DW1	.000000	467.588900
DW2	.000000	492.072200
DW3	.000000	562.961500
DW4	.000000	907.190400
DW5	.000000	866.404300
DX1	50.000000	.000000
DX2	50.000000	.000000
DX3	50.000000	.000000
DX4	50.000000	.000000
DX5	50.000000	.000000
H1	92000.000000	.000000
H2	95000.000000	.000000
H3	98000.000000	.000000
H4	101000.000000	.000000
H5	104000.000000	.000000

SMH1	61317.300000	.000000
SMH2	63234.600000	.000000
SMH3	65151.900000	.000000
SMH4	67069.200000	.000000
SMH5	69086.500000	.000000
PMH1	31587.700000	.000000
PMH2	32702.900000	.000000
PMH3	33563.100000	.000000
PMH4	34336.600000	.000000
PMH5	35538.500000	.000000
TH1	92905.000000	.000000
TH2	95937.500000	.000000
TH3	98715.000000	.000000
TH4	101405.800000	.000000
TH5	104625.000000	.000000
MV1	5824541.000000	.000000
MV2	6357394.000000	.000000
MV3	7006358.000000	.000000
MV4	8828179.000000	.000000
MV5	9624225.000000	.000000
LC1	277109.600000	.000000
LC2	315150.800000	.000000
LC3	330851.700000	.000000
LC4	403552.900000	.000000
LC5	439961.800000	.000000
HC1	276246.600000	.000000
HC2	328029.700000	.000000
HC3	381851.300000	.000000
HC4	566077.700000	.000000
HC5	647774.900000	.000000
TC1	553356.500000	.000000
TC2	643180.700000	.000000
TC3	712703.100000	.000000
TC4	969631.400000	.000000
TC5	1087737.000000	.000000
PRO1	5271184.000000	.000000
PRO2	5726714.000000	.000000
PRO3	6293655.000000	.000000
PRO4	7858548.000000	.000000
PRO5	8536492.000000	.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	.000000	4840.000000
3)	.000000	4791.000000
4)	.000000	4804.000000
5)	.000000	8923.000000
6)	.000000	8558.000000
7)	.000000	5668.765000
8)	.000000	5846.254000
9)	.000000	6501.166000
10)	.000000	9632.145000
11)	.000000	9716.354000
12)	.000000	5102.278000
13)	.000000	5370.220000
14)	.000000	5314.719000
15)	.000000	8815.637000
16)	.000000	8695.724000
17)	.000000	5608.365000
18)	.000000	5621.034000
19)	.000000	5672.599000
20)	.000000	9905.190000
21)	.000000	9757.404000
22)	.000000	.000000
23)	.000000	.000000
24)	.000000	.000000
25)	.000000	.000000

26)	.000000	.000000
27)	10000.000000	.000000
28)	14029.730000	.000000
29)	.000000	32.486840
30)	.000000	31.144740
31)	.000000	30.993420
32)	.000000	23.203950
33)	.000000	46.626090
34)	14110.340000	.000000
35)	.000000	29.775640
36)	.000000	28.647440
37)	.000000	29.211540
38)	.000000	23.115390
39)	.000000	45.711860
40)	13877.580000	.000000
41)	.000000	26.800000
42)	.000000	25.656250
43)	.000000	27.150000
44)	.000000	22.487500
45)	.000000	44.847110
46)	8000.000000	.000000
47)	5000.000000	.000000
48)	5000.000000	.000000
49)	411.363600	.000000
50)	5000.000000	.000000
51)	.000000	28.028920
52)	5000.000000	.000000
53)	2000.000000	.000000
54)	1527.237000	.000000
55)	.000000	.994118
56)	3000.000000	.000000
57)	.000000	28.112840
58)	.000000	.000000
59)	.000000	.000000
60)	.000000	.000000
61)	.000000	.000000
62)	.000000	.000000
63)	.000000	.000000
64)	.000000	.000000
65)	.000000	.000000
66)	.000000	.000000
67)	.000000	.000000
68)	.000000	.000000
69)	.000000	.000000
70)	.000000	.000000
71)	.000000	.000000
72)	.000000	.000000
73)	.000000	.000000
74)	.000000	.000000
75)	.000000	.000000
76)	.000000	.000000
77)	.000000	.000000
78)	.000000	.000000
79)	.000000	.000000
80)	.000000	.000000
81)	.000000	.000000
82)	.000000	.000000
83)	.000000	.000000
84)	.000000	.000000
85)	.000000	.000000
86)	.000000	.000000
87)	.000000	.000000
88)	.000000	.000000
89)	.000000	.000000
90)	.000000	.000000
91)	.000000	.000000
92)	.000000	.000000
93)	.000000	.000000

94)	.000000	.000000
95)	.000000	.000000
96)	.000000	.000000
97)	.000000	.000000

NO. ITERATIONS= 1688

RANGES IN WHICH THE BASIS IS UNCHANGED:

	OBJ COEFFICIENT RANGES		
VARIABLE	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
AS1	4840.000000	3527.000000	993.489700
AS2	4791.000000	3606.000000	1105.456000
AS3	4804.000000	3598.000000	1077.880000
AS4	4817.000000	4106.000000	INFINITY
AS5	4746.000000	3812.000000	INFINITY
AT1	9778.000000	INFINITY	809.338900
AT2	9436.000000	INFINITY	1018.268000
AT3	9092.000000	INFINITY	879.905500
AT4	8788.000000	135.000000	INFINITY
AT5	8428.000000	130.000000	INFINITY
AU1	9574.000000	INFINITY	682.300800
AU2	9260.000000	INFINITY	915.068300
AU3	8909.000000	INFINITY	767.081100
AU4	8585.000000	338.000000	INFINITY
AU5	8558.000000	169.000000	130.000000
AV1	9551.000000	INFINITY	630.957900
AV2	9348.000000	INFINITY	798.850000
AV3	9148.000000	INFINITY	599.999100
AV4	8923.000000	6783.000000	135.000000
AV5	8727.000000	INFINITY	169.000000
AW1	8367.000000	INFINITY	449.832300
AW2	8397.000000	INFINITY	465.231900
AW3	8402.000000	INFINITY	526.747600
AW4	8396.000000	527.000000	INFINITY
AW5	8258.000000	300.000000	INFINITY
AX1	15564.000000	449.981000	10724.000000
AX2	15579.000000	464.516200	10788.000000
AX3	15657.000000	526.010400	10853.000000
AX4	15706.000000	291.467000	6783.000000
AX5	15783.000000	308.312400	7225.000000
BS1	1410.000000	4258.765000	INFINITY
BS2	1467.000000	4379.254000	INFINITY
BS3	1517.000000	4984.166000	INFINITY
BS4	1388.000000	8244.145000	INFINITY
BS5	2411.000000	7305.354000	INFINITY
BT1	9280.000000	1034.384000	INFINITY
BT2	8996.000000	1227.274000	INFINITY
BT3	8711.000000	1863.765000	INFINITY
BT4	8426.000000	1206.145000	INFINITY
BT5	8141.000000	1575.354000	INFINITY
BU1	9209.000000	913.462600	INFINITY
BU2	8913.000000	1144.427000	INFINITY
BU3	8578.000000	1822.916000	INFINITY
BU4	8285.000000	1347.145000	INFINITY
BU5	8215.000000	1501.354000	INFINITY
BV1	9309.000000	791.824400	INFINITY
BV2	8982.000000	1158.351000	INFINITY
BV3	8658.000000	1969.965000	INFINITY
BV4	8349.000000	1283.145000	INFINITY
BV5	8055.000000	1822.401000	INFINITY
BW1	8077.000000	909.929600	INFINITY
BW2	8042.000000	1202.216000	INFINITY
BW3	7985.000000	1934.265000	INFINITY
BW4	7663.000000	1969.145000	INFINITY

BW5	7716.000000	2000.354000	INFINITY
BX1	15740.000000	INFINITY	791.824400
BX2	16040.000000	INFINITY	1144.427000
BX3	16816.000000	INFINITY	1822.916000
BX4	16275.000000	INFINITY	1206.145000
BX5	16604.000000	INFINITY	1501.354000
CS1	4014.000000	1088.278000	INFINITY
CS2	3983.000000	1387.220000	INFINITY
CS3	3834.000000	1480.719000	INFINITY
CS4	3773.000000	5042.637000	INFINITY
CS5	3518.000000	5177.724000	INFINITY
CT1	8178.000000	1310.002000	INFINITY
CT2	7870.000000	1609.259000	INFINITY
CT3	7541.000000	1552.519000	INFINITY
CT4	7241.000000	1574.637000	INFINITY
CT5	6925.000000	1770.724000	INFINITY
CU1	8388.000000	918.817900	INFINITY
CU2	8103.000000	1220.566000	INFINITY
CU3	8080.000000	852.250500	INFINITY
CU4	8148.000000	667.636700	INFINITY
CU5	8427.000000	268.723600	INFINITY
CV1	8726.000000	560.390300	INFINITY
CV2	8459.000000	942.412500	INFINITY
CV3	8186.000000	956.869200	INFINITY
CV4	7905.000000	910.636700	INFINITY
CV5	7736.000000	1106.853000	INFINITY
CW1	7671.000000	563.811200	INFINITY
CW2	7578.000000	982.143400	INFINITY
CW3	7479.000000	1006.457000	INFINITY
CW4	7360.000000	1455.637000	INFINITY
CW5	7124.000000	1571.724000	INFINITY
CX1	14614.000000	INFINITY	560.390300
CX2	14924.000000	INFINITY	942.412500
CX3	14912.000000	INFINITY	852.250500
CX4	14982.000000	INFINITY	667.636700
CX5	14993.000000	INFINITY	268.723600
DS1	4576.000000	1032.365000	INFINITY
DS2	4450.000000	1171.034000	INFINITY
DS3	4519.000000	1153.599000	INFINITY
DS4	4461.000000	5444.190000	INFINITY
DS5	4380.000000	5377.404000	INFINITY
DT1	9900.000000	841.286400	INFINITY
DT2	9457.000000	1077.014000	INFINITY
DT3	9315.000000	940.399000	INFINITY
DT4	9012.000000	893.190400	INFINITY
DT5	8708.000000	1049.404000	INFINITY
DU1	9820.000000	709.233700	INFINITY
DU2	9380.000000	967.860700	INFINITY
DU3	9240.000000	819.817900	INFINITY
DU4	8940.000000	965.190400	INFINITY
DU5	8934.000000	823.404300	INFINITY
DV1	9804.000000	701.325900	INFINITY
DV2	9596.000000	844.937500	INFINITY
DV3	9674.000000	641.249100	INFINITY
DV4	9580.000000	325.190400	INFINITY
DV5	9441.000000	500.316100	INFINITY
DW1	8807.000000	467.588900	INFINITY
DW2	8943.000000	492.072200	INFINITY
DW3	8955.000000	562.961500	INFINITY
DW4	8998.000000	907.190400	INFINITY
DW5	8891.000000	866.404300	INFINITY
DX1	16752.000000	INFINITY	467.588900
DX2	17049.000000	INFINITY	492.072200
DX3	17288.000000	INFINITY	562.961500
DX4	17473.000000	INFINITY	325.190400
DX5	17629.000000	INFINITY	500.316100
H1	.000000	.000000	INFINITY
H2	.000000	.000000	INFINITY

H3	.000000	.000000	INFINITY
H4	.000000	.000000	INFINITY
H5	.000000	.000000	INFINITY
SMH1	.000000	INFINITY	31.884060
SMH2	.000000	INFINITY	30.629080
SMH3	.000000	INFINITY	29.831100
SMH4	.000000	INFINITY	53.863330
SMH5	.000000	INFINITY	50.111260
PMH1	.000000	INFINITY	61.892590
PMH2	.000000	INFINITY	59.456440
PMH3	.000000	INFINITY	57.907420
PMH4	.000000	INFINITY	104.558200
PMH5	.000000	INFINITY	97.560420
TH1	.000000	INFINITY	21.043480
TH2	.000000	INFINITY	20.215190
TH3	.000000	INFINITY	19.688520
TH4	.000000	INFINITY	35.549800
TH5	.000000	INFINITY	33.106380
MV1	.000000	.015967	.012705
MV2	.000000	.027373	.015006
MV3	.000000	.011643	.011370
MV4	.000000	.008675	.033787
MV5	.000000	.021958	.012684
LC1	.000000	.881611	.906024
LC2	.000000	1.437432	1.079735
LC3	.000000	.985948	.481358
LC4	.000000	.443479	.463156
LC5	.000000	.427405	.640869
HC1	.000000	.876173	3.306237
HC2	.000000	.824489	3.157541
HC3	.000000	.580209	3.059035
HC4	.000000	.413849	.407461
HC5	.000000	.155642	.582116
TC1	.000000	.902613	2.800570
TC2	.000000	.815851	2.656678
TC3	.000000	.590925	2.552115
TC4	.000000	.408341	.407461
TC5	.000000	.159184	.582096
PRO1	.000000	.124272	.090233
PRO2	.000000	.031170	.059982
PRO3	.000000	.029399	.016135
PRO4	.000000	.012539	.012360
PRO5	.000000	.011767	.030078

RIGHTHAND SIDE RANGES

ROW	CURRENT RHS	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	200.000000	179.868300	12.439360
3	200.000000	176.379300	11.120710
4	200.000000	169.238800	13.688020
5	200.000000	2.493113	27.809920
6	200.000000	8.983748	2.780957
7	90.000000	24.583330	13.245620
8	90.000000	30.291480	11.769000
9	90.000000	44.782610	14.402170
10	90.000000	2.545710	28.396630
11	90.000000	9.423769	2.917167
12	75.000000	26.029410	14.024770
13	75.000000	32.320570	12.557350
14	75.000000	48.130840	15.478970
15	75.000000	2.742424	30.590910
16	75.000000	10.307250	3.190651
17	50.000000	22.217570	11.970930

18	50.000000	27.020000	10.497950
19	50.000000	39.768340	12.789580
20	50.000000	2.234568	24.925930
21	50.000000	8.245798	2.552521
22	92000.000000	10000.000000	92000.000000
23	95000.000000	10000.000000	95000.000000
24	98000.000000	10000.000000	98000.000000
25	101000.000000	10000.000000	101000.000000
26	104000.000000	10000.000000	104000.000000
27	500000.000000	INFINITY	10000.000000
28	15000.000000	INFINITY	14029.730000
29	5000.000000	1890.783000	5000.000000
30	5000.000000	1890.783000	5000.000000
31	5000.000000	1890.783000	5000.000000
32	10000.000000	1890.783000	10000.000000
33	52000.000000	2861.053000	5310.000000
34	15000.000000	INFINITY	14110.340000
35	5000.000000	1734.830000	5000.000000
36	5000.000000	1734.830000	5000.000000
37	5000.000000	1734.830000	5000.000000
38	10000.000000	1734.830000	10000.000000
39	55000.000000	2624.487000	6755.000000
40	15000.000000	INFINITY	13877.580000
41	5000.000000	2190.083000	5000.000000
42	5000.000000	2190.083000	5000.000000
43	5000.000000	2190.083000	5000.000000
44	8000.000000	2190.083000	8000.000000
45	60000.000000	3312.500000	10300.000000
46	8000.000000	INFINITY	8000.000000
47	5000.000000	INFINITY	5000.000000
48	5000.000000	INFINITY	5000.000000
49	5000.000000	INFINITY	411.363600
50	5000.000000	INFINITY	5000.000000
51	93000.000000	6730.000000	603.333400
52	5000.000000	INFINITY	5000.000000
53	2000.000000	INFINITY	2000.000000
54	2000.000000	INFINITY	1527.237000
55	3000.000000	472.762600	1527.237000
56	3000.000000	INFINITY	3000.000000
57	99000.000000	714.705900	2308.823000
58	.000000	61317.300000	INFINITY
59	.000000	63234.600000	INFINITY
60	.000000	65151.900000	INFINITY
61	.000000	67069.200000	INFINITY
62	.000000	69086.500000	INFINITY
63	.000000	31587.700000	INFINITY
64	.000000	32702.900000	INFINITY
65	.000000	33563.100000	INFINITY
66	.000000	34336.600000	INFINITY
67	.000000	35538.500000	INFINITY
68	.000000	92905.000000	INFINITY
69	.000000	95937.500000	INFINITY
70	.000000	98715.000000	INFINITY
71	.000000	101405.800000	INFINITY
72	.000000	104625.000000	INFINITY
73	.000000	5046566.000000	INFINITY
74	.000000	6121172.000000	INFINITY
75	.000000	10130900.000000	INFINITY
76	.000000	9866280.000000	INFINITY
77	.000000	6725955.000000	INFINITY
78	.000000	274597.600000	INFINITY
79	.000000	302049.800000	INFINITY
80	.000000	286654.700000	INFINITY
81	.000000	398771.400000	INFINITY
82	.000000	529839.300000	INFINITY
83	.000000	276246.600000	INFINITY
84	.000000	328029.700000	INFINITY
85	.000000	381851.300000	INFINITY

86	.000000	566077.700000	INFINITY
87	.000000	647774.900000	INFINITY
88	.000000	553356.500000	INFINITY
89	.000000	630680.700000	INFINITY
90	.000000	712703.100000	INFINITY
91	.000000	969631.400000	INFINITY
92	.000000	1087737.000000	INFINITY
93	.000000	5271184.000000	INFINITY
94	.000000	5710758.000000	INFINITY
95	.000000	5832418.000000	INFINITY
96	.000000	7495572.000000	INFINITY
97	.000000	5925346.000000	INFINITY